EPITOME

OF

SPACE MEDICINE

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USAF SCHOOL OF AVIATION MEDICINE
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ON THE PHYSICAL PROCESS OF EXPLOSIVE DECOMPRESSION

FRITZ HABER, Ph.D.

DEPARTMENT OF SPACE MEDICINE

SPECIAL REPORT

USAF SCHOOL OF AVIATION MEDICINE
RANDOLPH FIELD, TEXAS
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ON THE PHYSICAL PROCESS OF EXPLOSIVE DECOMPRESSION

The problems of explosive decompression have long been recognized in Aviation Medicine and have been the subject of intense research. Because of difficulties inherent in actual experiments in aircraft, experiments were confined to the laboratory, where simulation devices were applied. In these devices air is caused to rush from a small separate parasite chamber into a larger evacuated chamber by suddenly throwing open a valve in the tube connecting the two chambers. Some calculations based on laws of aerodynamics are necessary for relating the experimental results to the actual event as it may occur in the aircraft.* These calculations contain the ratio of size of the two chambers, the cross-section of the valve, and the initial pressure in both chambers.

It seems important to consider two facts which have an influence on the physical phenomena of explosive decompression:

1 Influence of the air's humidity.

2. Rate of change of temperature.

1. *Influence of Humidity.*

Normal air always contains water vapor. Since the temperature drops as a consequence of a sudden decrease of pressure, the dewpoint is reached at a certain instant during the course of decompression. Consequently condensation of water vapor (i.e., formation of fog) sets in; this phenomenon is invariably observed during decompression experiments in the laboratory. Such a process of condensation, however, can occur only in conjunction with the release of considerable heat, namely, the heat of vaporization. For instance, the cooling of 1 kg. of air saturated with water vapor from 15° C. to 5° C. will be followed by condensation of 5.4 gm. of water, releasing 3.2 kcal of heat. This heat is sufficient to raise the temperature of 1kg. of air by about 13° C.

As a consequence of this heating the decompression of moist air will be associated with a smaller drop in temperature as compared to the decompression of dry air. Since the escape velocity through the orifice is related to the temperature and is higher at higher temperatures (see appendix), it can be stated that the time of evacuation will be shortened.

This rough survey shows that humidity has a decisive influence upon the process of decompression of air. However, the physical process of decompression cannot be represented by an analytical mathematical expression if the air's humidity is to be considered. Such a calculation must be accomplished stepwise, since the ratio of specific heats, $K = \frac{c_p}{c_v}$ is not a constant but depends on the temperature. Thus, the value of K is about 1.1 at room temperature and 100 percent humidity, and it approaches the dry air's value of 1.4 with decreasing temperature.

In figure 1 the result of a calculation of explosive decompression is represented concerning an initial state of the air characterized by 20° C. and 70 percent humidity and concerning escape into a vacuum through an orifice of an effective cross-section of 1 cm.^{2} per 1 m.^{3} of volume of the cabin. A comparison of these results to calculations that are valid for absolutely dry air under the same conditions shows that the time required for evacuation becomes shortened by about 15 percent if the air is moist. Because of the faster evacuation effected by these phenomena the problems of time of useful consciousness, or time reserve, are aggravated.

Figure 2 shows the temperature as a function of time during explosive decompression under the same conditions as in figure 1. The difference between the temperature curves, obtained with dry and moist air, is obvious. It may be further noted that the functions represented in figure 2 hold only if there is no exchange of heat between the air and the wall of the cabin. This assumption seems to be justified, considering the short time required for evacuation.

*AIR TECHNICAL SERVICE COMMAND MEMORANDUM REPORT NO. TSEAL-3-695-29M by A.P. Gagge, 2 July 1945.

2. *Rate of Change of Temperature.*

The heat exchange plays an important role, however, if the temporal change of temperature after the decompression is considered. The temperature is very low at the first instant but approaches that of the environment after a certain time. Theoretically, the temperature change differs in experimental, as compared with actual, explosive decompressions, as follows:

a. Experiment in the low pressure-chamber. Even if there is no exchange of heat, the temperature must return to its initial value by the time the movement of the air ceases. This is a consequence of the fact that no work is done by the air within the enclosed system of the two chambers. The temperature remains below its initial value only so long as the air is moving and hence possesses kinetic energy.

b. Explosive decompression in an aircraft's cabin. In this event, the final temperature of the cabin's air is determined by the temperature of the ambient air, and it will assume this value after a certain time.

In both cases, however, the air of the cabin will be heated by the heat exchange between wall and air of the cabin, practically reaching the temperature of the wall. This process develops very quickly and is practically completed after 10-15 seconds, even if the difference in temperature is 100° C. This was evidenced by measurements during explosive decompression in a low pressure-chamber.* Results are given in figure 3. By an over-all calculation of the constants of heat exchange, values in the the order of $5 - 10 \frac{\text{kcal}}{\text{m}^2 \cdot {}^\circ\text{C} \cdot \text{h}}$ were obtained. These figures are quite normal. Moreover, figure 3 shows the remarkable fact that an explosive decompression from sea level up to 50,000 ft. is associated with a short drop in temperature of almost 100° C. It is of some interest that no test subject experiencing explosive decompression has ever been aware of this sharp drop in temperature.

SUMMARY

The calculations, published to date, concerning the physical process of explosive decompression deal with absolutely dry air only. It is here shown that the air's humidity shortens the time of evacuation. Moreover, it is shown by calculation and experiment that the temporal change of temperature after decompression is decisively influenced by the temperature of the ambient wall. The air of the cabin assumes this temperature within a short time. Actual measurements give evidence of a transient drop in temperature of about 100° C. associated with explosive decompression.

*The experiments were carried out in cooperation with H. G. Clamann, M.D., USAF School of Aviation Medicine, Randolph Field, Texas.

APPENDIX

The mass dm escaping through the area A within the time dt is given by:

$$dm = -\rho \cdot c \cdot A \cdot dt \qquad (1)$$

whence c represents the velocity of the gas and ρ its density. If the cabin's volume is designated by V, we have $dm = V \cdot d\rho$. The velocity c, with which the air escapes into the vacuum, is closely related to the velocity a of the sound.

$$c = \sqrt{\frac{2}{K-1}} \cdot a = \sqrt{\frac{2K}{K-1} \cdot g \cdot R \cdot T} \qquad (2)$$

whence K is the ratio $\frac{c_p}{c_v}$ of the specific heats, g the acceleration of gravity, R the gas constant and T the temperature in degrees Kelvin. Then equation (1) becomes:

$$\frac{d\rho}{\rho} = -\sqrt{\frac{2K}{K-1} \cdot g \cdot R \cdot T} \cdot \frac{A}{V} \cdot dt \qquad (3)$$

For adiabatic changes of gas states the following relation holds:

$$\rho = \rho_0 \left(\frac{T}{T_0}\right)^{\frac{1}{K-1}}$$

or

$$\frac{d\rho}{\rho} = \frac{1}{K-1} \frac{dT}{T} \qquad (4)$$

Introducing equation (4) into equation (3) yields the relation between temperature and time

$$dt = -\frac{\frac{V}{A}}{\sqrt{K\cdot(K-1)\cdot 2g\cdot R}}\cdot\frac{dT}{T^{3/2}} \qquad (5)$$

The value of K depends on the temperature in the case of humid air. It can be determined in the following fashion. If x in kg/kg represents the water vapor content of moist air, and r the heat of vaporization, the heat dq will be transferred subsequent to a change of temperature dT. The heat dq is given by:

$$d_q = r\cdot dx = r\cdot\frac{dx}{dT}\cdot dT$$

Consequently the heat required to raise the temperature of humid air, keeping its volume constant, is given by:

$$dQ = c_v\cdot dT + r\cdot\frac{dx}{dT}\cdot dT = [c_v + r\cdot\frac{dx}{dT}]\cdot dT$$

The same holds for the specific heat c_p (with constant pressure), so that the ratio K assumes the value K'

$$K' = \frac{c_p + r\cdot\frac{dx}{dT}}{c_v + r\cdot\frac{dx}{dT}}$$

The values of K' as a function of temperature are shown in figure 4. The differential equation (5) cannot be solved, since K' is a variable. Therefore, one has to assume that K' is a constant for a small temperature range dT, for which the corresponding period of time dt can be computed according to equation (5). The function T = f (t) is then found by a process of summation. The pressure as a function of time is thus obtained, since pressure and temperature in adiabatic processes are related according to the following equation:

$$\left[\frac{T}{T_o}\right]^{\frac{K}{K-1}} = \frac{p}{p_o}$$

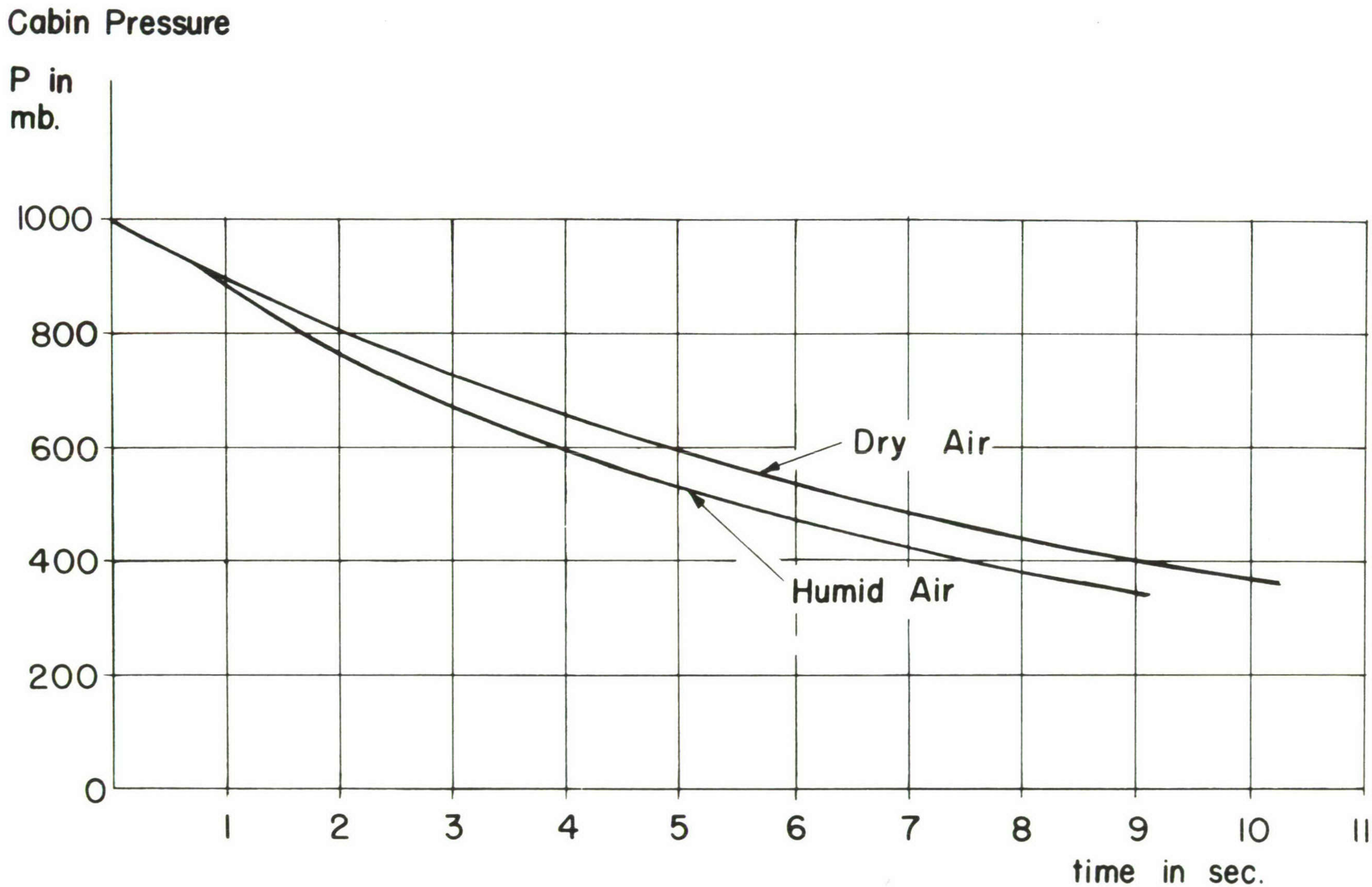

Figure 1

Cabin pressure as a function of time during explosive decompression into vacuum.

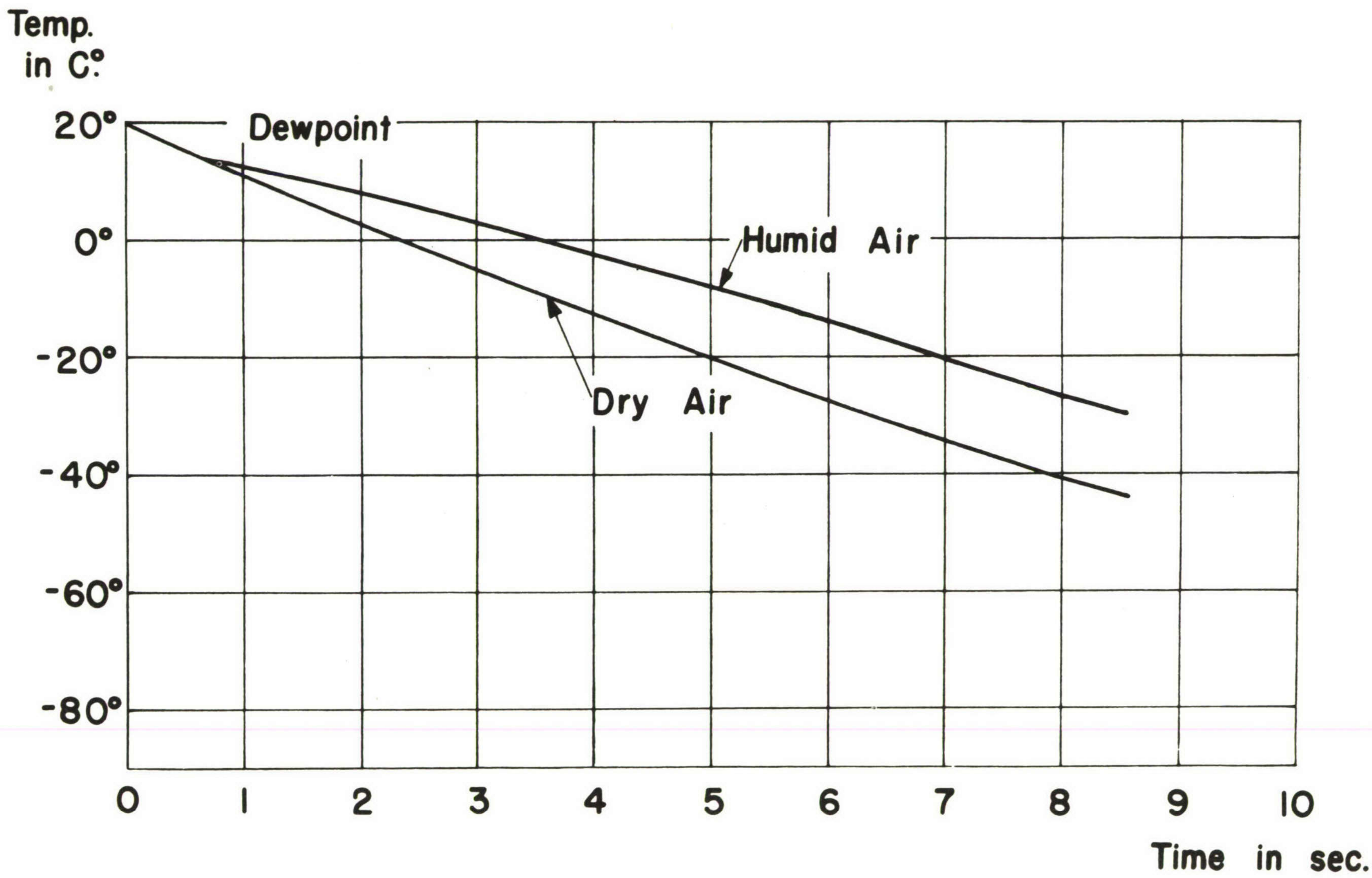

Figure 2

Temperature as a function of time during explosive decompression into vacuum.

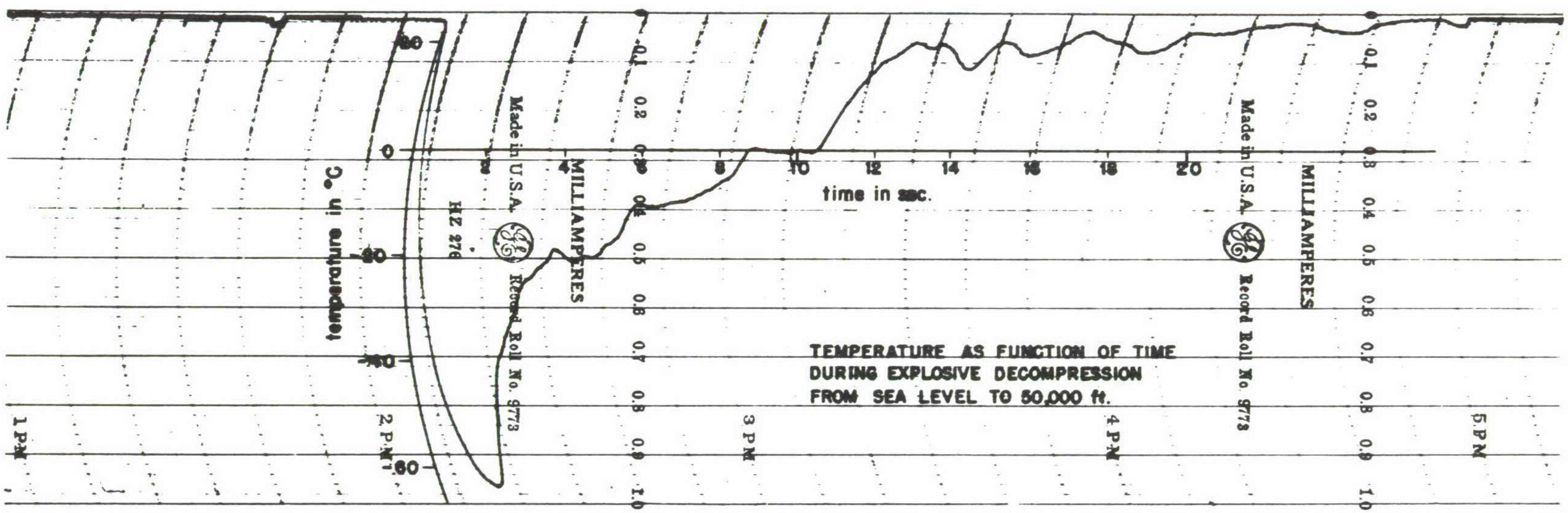

Figure 3

Record of measurements of temperature during explosive decompression in low pressure-chamber.

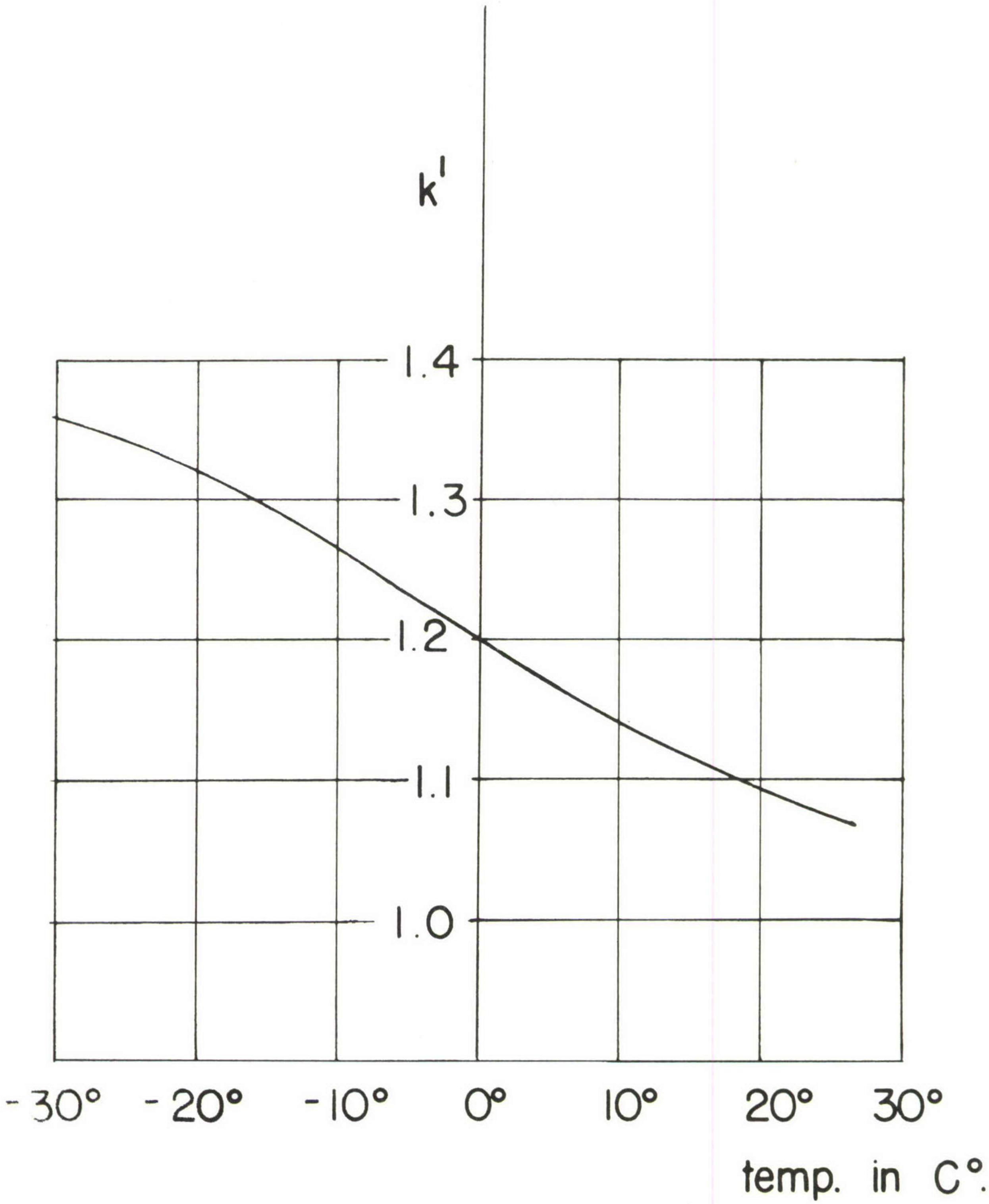

Figure 4
Ratio K' of specific heats of 100 percent moist air as a function of temperature.

Possible Methods of Producing the Gravity-free State for Medical Research

By Fritz Haber, Ph.D., and Heinz Haber, Ph.D.
Department of Space Medicine

Special Project

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Possible Methods of Producing the Gravity-free State for Medical Research

MODERN AIRCRAFT may soon fly at velocities of over 2,000 miles per hour in stratospheric altitudes. Such data remind the flight surgeon of medical problems which chiefly center around acceleration during maneuvers, pressurized cabins and explosive decompression.

Yet, these data also form the source of another problem, however less obvious, for the flight surgeon, namely, the occurrence of reduced gravity. Let us consider an aircraft of the above-mentioned type which flies parallel to the ground at a velocity of one kilometer per second, i.e., 3 Mach. Then we see that this craft travels around the center of the earth in a circular course, and, a brief calculation shows that about one sixtieth of the aircraft's weight is counteracted by the centrifugal force arising from this "rotatory" movement of the aircraft. The same holds true for the pilot: his original 150 pounds, for instance, are reduced to 147½ pounds. If the aircraft's velocity would be tripled, the amount of this reduction of weight would become noticeable; it would amount to not less than 15 per cent. Figure 1 shows the relationship between velocity of the aircraft and the prevailing gravity under these circumstances.

Fig. 1.

It further becomes evident that the occurrence of reduced gravity in modern aircraft is favored also by the extreme altitudes in which these crafts cruise. This effect is not produced by the decrease of terrestrial gravitation with increasing altitude, as one might be led to believe. At an altitude of 100,000 feet, for instance, terrestrial gravity still amounts to more than 99 per cent of its value at sea level. It is the density of the air at this altitude which is responsible for the effect now under consideration; for, at that height, the density of the air is only one hundredth of the corresponding value at sea level. As a consequence, an aircraft cruising at 100,000 feet will negligibly be disturbed in its free motion as soon as the drive is throttled. This means that the pilot will find

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himself in an almost ideal state of free fall in all maneuvers involving throttling of the drive. The state of free fall, however, is mechanically characterized by the fact that the resultant of all forces acting on the pilot vanishes. Consequently, the pilot is put into the gravity-free state, or at least into a state of sharply reduced gravity as soon as he dares throttle his engine.

The duration of such states of reduced or eliminated gravity are still short: They are of the order of one-half to one minute. But one must consider this phenomenon as a medical problem, chiefly for two reasons:

1. Gravity as a physical factor of environment has the outstanding property of being omnipresent and everlasting. Not a single individual has as yet been away from its influence for more than one to two seconds.

2. Zero-gravity and sub-gravity will greatly gain importance as environmental factors of man, since the development of rocket craft points toward a rapid increase of velocities and altitudes in the not too distant future.

In view of this development we must not fail to direct our attention to possible effects of sub-gravity and zero-gravity on man. It is the purpose of this paper to present some theoretical considerations as to the procurement of means suitable for studying the medical phenomena associated with the lack of weight.

In medical research, the principle of simulation is almost exclusively applied for studies related to influences of physical environmental factors on the living organism. For this, the low pressure chamber and the human centrifuge are the most outstanding examples in aviation medicine. However, confronted with the necessity of producing states of sub-gravity and zero-gravity we must concede that all tricks of simulation fail. The means required for the elimination of gravity are quite involved, and, it is for this reason that no experiments have as yet been attempted to eliminate or even reduce gravity for the purpose of medical research.

Before entering the discussion on the possibilities of the elimination of gravity we are to concern ourselves with the various aspects of the phenomenon of weight. Within the gravitational field of the earth, a body derives its weight from the mechanical support that prevents it from falling freely. A body is weightless as soon as it is allowed to move freely under the influence of gravitation and of its own inertia. Every fashion of support, including frictional forces from the ambient air and propelling forces from an engine, restores the body's weight either partly or entirely. As a consequence, within the gravitational field of the earth, gravity can be reduced or removed by kinematic means only.

The simplest means to this end consists of the realization of the state of vertical free fall. If a body moves vertically downward at an acceleration of 1 g, an upward acting force of inertia becomes effective which exactly compensates the body's weight. It is true, owing to the velocities soon to be reached by a free falling body, strong frictional forces from the air will arise, so that the body's weight will soon be restored because of the support from these frictional forces. Speaking in terms of kinematics, the acceleration of 1 g cannot be maintained for any appreciable length of time and the velocity of the falling body approaches a certain constant value. With the vanishing acceleration the force of inertia pulling upward expires also, so that the body's weight will be restored.

From these conditions it can be derived that friction from the air makes the exploitation of a free-fall-missile difficult for our purposes. At the least, it would be required to drop the missile from a balloon; for, the initial

translatory motion of the missile, if dropped from an aircraft, would give rise to considerable frictional forces from the air resulting in considerable deceleration from the start. There are a score of other problems which stem from the necessity of braking the missile's fall by means of parachutes; the difficulties involved in the recovery of the missile; and the considerable preparations required for a single experiment.

The possibilities of utilizing the vertical motion, for our purpose, however, are not exhausted with the failure of the free-fall-missile. There is a means which permits reduction of a body's support by a constant amount for a certain period of time, namely, the elevator. If the elevator is at rest, the weight of the elevator car is exactly equal to the tension of the rope. If the tension of the rope is decreased by a certain fraction of the suspended weight, the elevator car will be deprived of that same fraction of its support. According to the mechanical principles outlined above, the car and everything it contains will then be transposed into a state of sub-gravity. Speaking in terms of kinematics, the elevator car will move downward at a certain acceleration a, whence $a<g$. As long as these kinematic and dynamic conditions can be maintained, the passengers of the elevator car will find themselves in a state of sub-gravity of the amount g-a. The durations of such states of sub-gravity which can be attained in this manner, depend chiefly upon the maximum permissible velocity of the elevator car. Furthermore, the height of the elevator shaft will be of importance, since longer braking distances and consequently higher velocities are permissible in long-shaft-elevators.

From the laws of kinematics it can be followed that the acceleration only must be kept constant in experiments of this kind, i.e., one is free to begin the motion of the elevator with any initial velocity desired. Consequently one is able to double the duration of the various states of sub-gravity by starting the experiment with the largest velocity the elevator car can attain in an upward motion. A state of sub-gravity characterized by the value g-a is produced by superimposing a downward acceleration "a" on the motion of the elevator car. This is done by decreasing the tension of the rope by a proper amount, and the passengers of the elevator remain in this

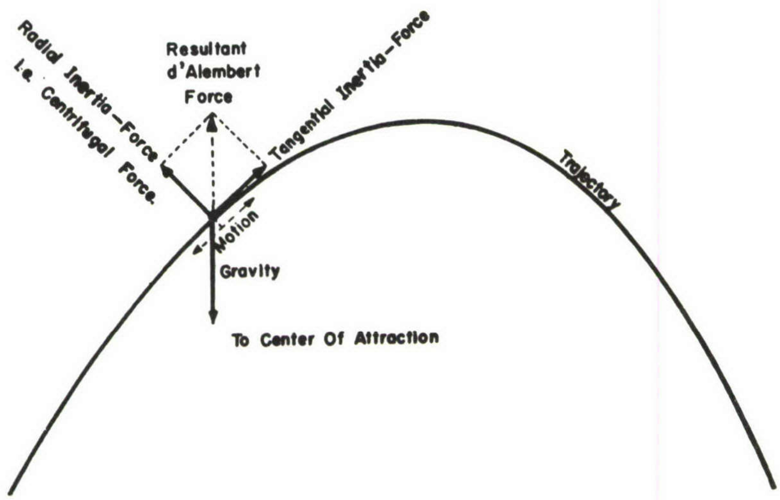

Fig. 2.

state of sub-gravity as long as these conditions of the rope's tension can be maintained. Under these conditions the motion of the elevator car is such that the upward velocity will gradually be consumed by the superimposed downward acceleration; after having reached the peak, the car starts to drop and reverses the pattern of motion in its downward course.

By applying this method states of sub-gravity between 0.9 g and 0.7 g can be produced for five to twenty-five seconds using long-shaft-elevators of skyscrapers. The durations obtainable with this means are short; yet, the elevator method appears to be worth while for a selected number of medical problems under sub-gravity conditions. This is especially true in view of the ease of access to elevators, the ease of operation and the number of experiments that can be carried out within a short time.

In directing our attention to the entire elimination of gravity we can state the following requirements a means to this end must fulfill:

1. The means must be equipped with a controllable force in order to make it capable of overcoming and eliminating the support originating in friction from the air.

2. The means must be able to cope with high velocities which it must attain and subsequently break down.

The modern aircraft is such a means.

The aircraft, in contrast to the elevator, is not limited to a single dimension, namely the vertical, in its motion. Consequently, the initial component of velocity which can be superimposed to the component of acceleration, may assume any value regarding size and direction. A close examination of all factors involved shows that it is most profitable to select an initial velocity as large as possible at a large angle of climb. In order to eliminate gravity during such a flight, care must be taken that a constant downward acceleration of 1 g prevails during the entire flight. Similar to the case of the elevator, the upward vertical component of the aircraft's velocity will gradually be consumed by the downward acceleration; the vertical component of velocity vanishes at the peak of the trajectory and subsequently reverses its pattern. The horizontal component of velocity remains constant during the entire zero-gravity flight; it equals the aircraft's velocity at the start multiplied by the cosine of the angle of climb at that point.

The aforementioned characteristics

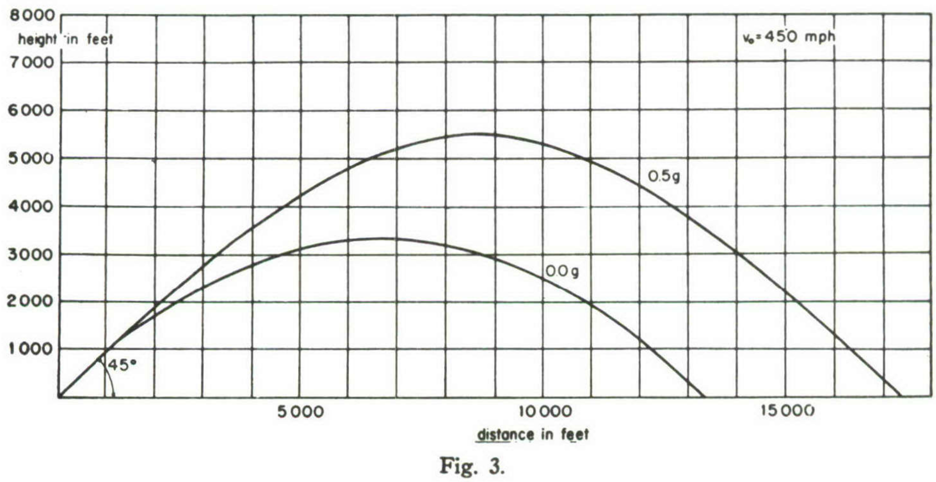

Fig. 3.

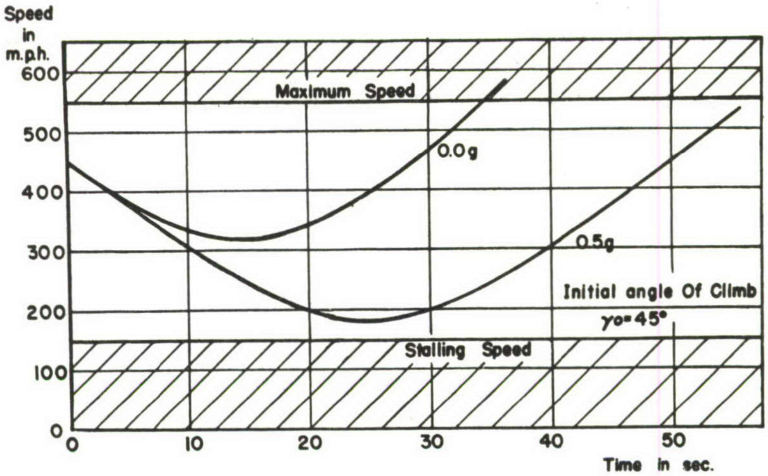

Fig. 4.

of the trajectory reveal that it is a parabola with vertical axis. In other words, the aircraft simulates the motion of a body hurled obliquely upward, if there would be no friction from the air. These are exactly the requirements for producing the gravity-free state. The body would move under the influence of terrestrial gravitation

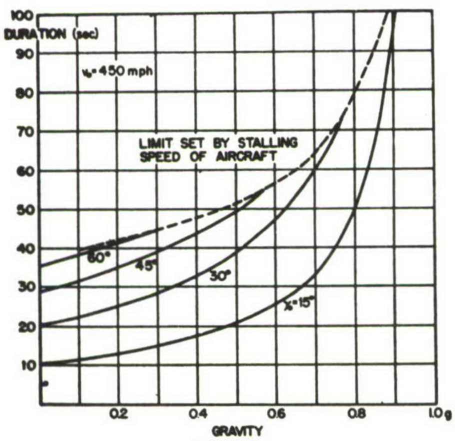

Fig. 5.

and of its own inertia only, undisturbed from any other outer force, it is then that it is weightless. In the case of the aircraft, the supporting force of friction from the air is eliminated by the power of the engines. Figure 2 demonstrates a scheme how the weight of a body moving along a vertical parabola is eliminated by the resultant of the forces of inertia.

Theoretically, the velocity of the aircraft has no part in the formation of sub-gravity and zero-gravity states; in our practical case, however, it plays a dominant role. Both the maximum permissible speed and the minimum stalling speed of the aircraft impose certain limitations on the duration of these states. The trajectories must be such that the velocities at the beginning and the end of the trajectory are not too large, and that the velocity at the peak of the trajectory is not too small.

The aircraft-method also affords the possibility of producing certain values of sub-gravity. As with the elevator, the motion of the aircraft must be characterized by a certain downward acceleration a, so that the passengers of the aircraft are exposed to an acceleration g-a. With this method, states of sub-gravity can be maintained for correspondingly longer periods of time.

The following figures demonstrate a number of numerical details as to zero-gravity and sub-gravity flights. Figure 3 shows the trajectories resulting from values of 0.0 g and 0.5 g, with a maximum velocity of 450 m.p.h., and an initial angle of climb of 45°. Figure 4 shows the corresponding velocities as a function of time exhibiting the limitations of the method

caused by the maximum and minimum velocities. Figure 5 shows the duration obtainable as a function of the amount of sub-gravity desired for various initial angles of climb.

The last figure demonstrates that gravity can be removed, exploiting present means, for about ten to thirty-five seconds. The durations obtainable for states of sub-gravity are correspondingly longer. Admittedly, as in the elevator, the periods are still short, but we may consider these periods long enough for investigations concerning selected medical problems, since any other method, such as a parachute jump from a balloon, does not remove gravity for more than one or one and one-half seconds. In contrast to this, the zero-g-aircraft affords durations of the gravity free state more than twenty times as long.

LIFE ON MARS IN VIEW OF PHYSIOLOGICAL PRINCIPLES

HUBERTUS STRUGHOLD, M.D., Ph.D.

DEPARTMENT OF SPACE MEDICINE

SPECIAL REPORT

USAF SCHOOL OF AVIATION MEDICINE
RANDOLPH FIELD, TEXAS
MARCH 1951

LIFE ON MARS IN VIEW OF PHYSIOLOGICAL PRICIPLES

During the last opposition of Mars in 1947–48, it was found that the infrared spectrum of the so-called green areas on that planet is compatible with the spectrum of lower plants (lichens and mosses) (Kuiper, 12). This finding has given new impetus to the discussion concerning the possibility of life on Mars, which was raised some seventy years ago (Schiaparelli, Lowell, and others). Understandably, these spectroscopic observations constitute a challenge to physiology, especially since more details concerning the constitution of the Martian atmosphere have recently been made available (12). Today, physiological considerations to this end can be derived from a rather broad background of knowledge, since during the past fifty years physiology and aviation medicine have made great progress in the study of the limits and stages of life. In particular, cold and hypoxia have been the subjects of intense research in aviation medicine (2, 22). Therefore, the problem of extraterrestrial life will be discussed on the basis of present physiological experience. Particular attenwill be given the environmental factors of temperature and oxygen because of their close interrelation in biological processes.

In the following discussion it is assumed that the laws of biological processes are the same in the entire universe, and that the structure of living matter is based on the carbon atom and its unique chemical properties.

It appears quite fruitful to study the question concerning life on planets from the viewpoint of the "law of the minimum" (G.V. Liebig) or the "principle of the limiting factors" as has been elaborated in greater detail by F.F. Blackman (4). In doing so we conform with common usage in terrestrial ecology and economic geography. In their simplest form these laws state that the environmental factors—such as temperature, light, water, and chemical components of soil and air—impose limits to life by being either excessively strong and abundant or too weak and sparse. A certain minimum must be reached and a certain maximum must not be exceeded; only within these limits can life exist and develop. Between these two cardinal points lies a third one, representing the optimum of an environmental condition or of a combination of such conditions, which is distinguished by being particularly favorable for the flourishment of life. Although these cardinal points, as was found later (4), are fluctuating greatly in relation to each other ("relatively limiting factors"), in the following study these principles will be applied in their simplest form to the planets and especially to Mars.

Let us start with *temperature* (figure 1). Active processes of life such as growth, metabolism, muscle and nerve activity, reproduction, etc., take place only within a temperature range (prevailing in the tissue) between a few degrees below the freezing point of water and about +55° to 60° C. Above this temperature living matter is transposed into the state of "heat rigor" and soon perishes (dehydration, blocking of enzyme action, coagulation of protein). Only the thermophilic bacteria are still capable of growing at temperatures up to 75° C. Spores of bacteria and certain seeds can survive if exposed to temperatures of +120° C. for several hours.

Below the minimum temperature required for active life lies the beginning of the lethal range for most organisms; yet, as is known, arctic plants easily survive temperatures down to −60° C. Thus it was found experimentally—by immersing the specimens in liquid nitrogen, oxygen, hydrogen, and even helium—that certain lower organisms such as algae, bacteria, lichens, and mosses are capable, for weeks, of withstanding temperatures closely approaching absolute zero. The living matter is hereby trans-

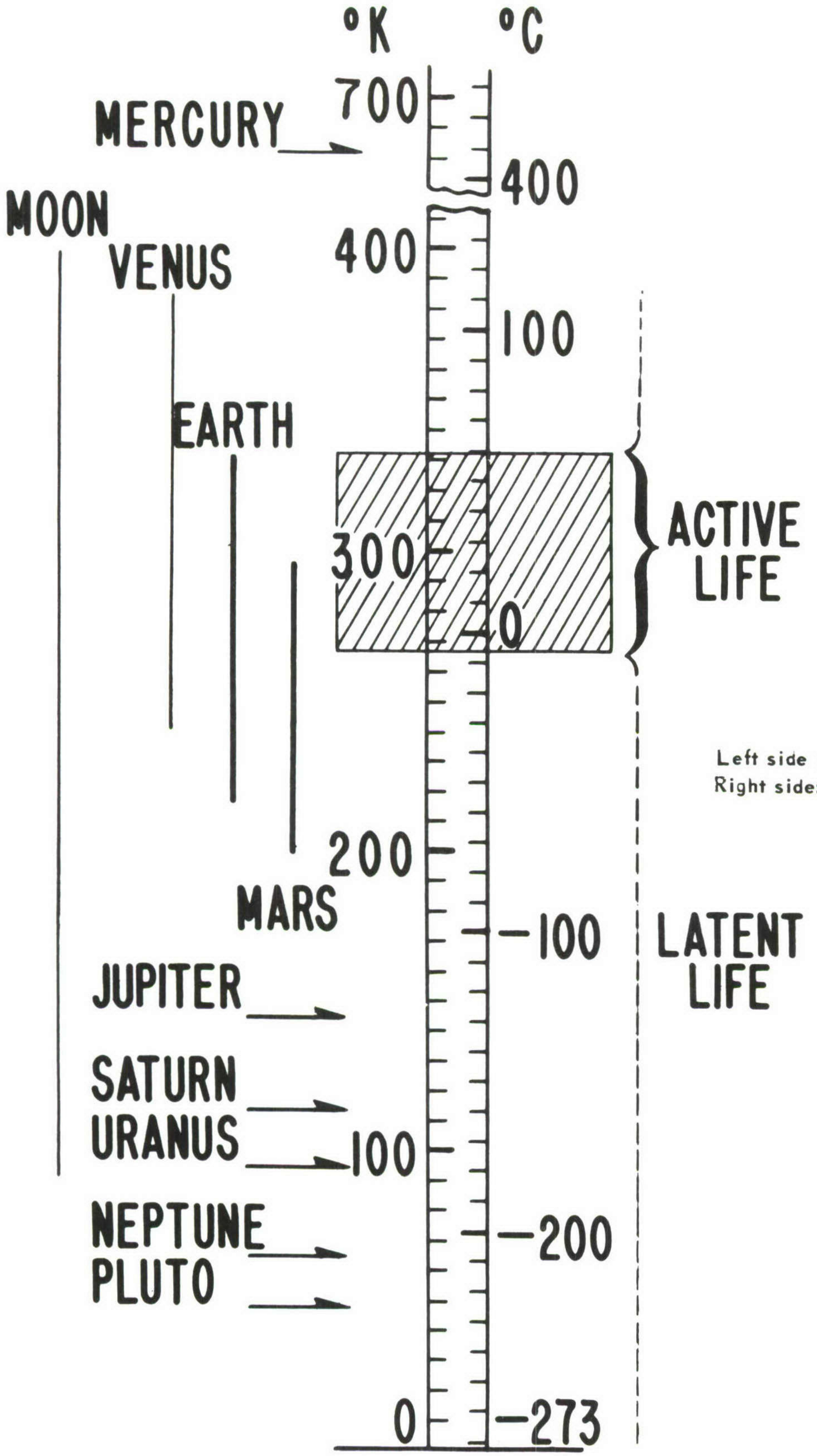

Figure 1
Left side : Surface temperatures of the planets.
Right side: Temperature scale of life.

posed into the state of "cold rigor" which also can be designated as the state of latent or dormant life. Summarizing, we can state that there is no decrease of temperature capable of destroying, unconditionally, every form of living matter, provided the onset of cold follows certain temporal patterns (11, 15).

If we now consider the temperatures found on the surface and in the atmospheres of the planets (24), we see that Mercury's temperature lies far above the maximum cardinal point, within the lethal range (see figure 1). Venus with more than 100° C. in its lower atmospheric layers and about −25° C. in its outermost stratum approaches biological temperatures only in certain higher strata. The temperatures found on earth ranging from −60° to +60° C. cover the entire range of active life with its upper half, while they also cover about 60 centigrades of the cold range of latent life. The Martian temperatures range with its upper quarter coincides with the lower part of the biothermal band and covers more than 60 centigrades of the cold range of latent life. The larger planets lie deep in the temperature range of latent life, in other words 150 to 200 centigrades below the temperature minimum for active life.

It may be added that the temperature of the moon varies between −150° and +100° C.

In conclusion the following may be said: From the standpoint of temperature, Mars and possibly Venus* are the only planets, aside from the Earth, which at present possess the prerequisites of life, in our sense. In this connection, it must be considered that in view of the large diurnal amplitudes of temperatures only eurythermal living beings can exist on Mars, i.e., those which can resist rapid changes of temperatures within a wide range. This physiological requirement also points toward certain lower organisms, such as algae, lichens, and mosses, which are characterized by pronounced eurythermia.

Mars might actually be considered a biophilic planet, in regard to temperature, but its combination of ecological conditions shows a very weak point: Oxygen cannot be found in the Martian atmosphere (1, 12).

Oxygen, apart from carbon, is the bioelement par excellence because (1) on the average, oxygen makes up 60 percent of the living matter (water included); and (2) the most important energy source of the organisms is biological oxidation (aerobic respiration). Another source of energy, though less significant, is anaerobic respiration which requires no oxygen. However, the substances undergoing anaerobic respiration consist of oxygen, to a rather large part.

The production of energy which is based on biological oxidation consumes large amounts of oxygen and requires a certain concentration of oxygen in the medium surrounding the organisms. For man, for instance, this concentration must be of the order of 5.5×10^{18} oxygen molecules per cm.^{3} of air. Physiologically, this concentration or the corresponding pressure is likewise limited by a maximum and a minimum; exceeding these limits is incompatible with life. In the following we are mainly interested in the *oxygen minimum* which is just sufficient to permit a "vita minima."

For man the minimum oxygen pressure is about 65 mm. Hg (corresponding to an altitude of 7,000 m.) (see figure 2). Acclimatization to altitudes of about 7,000 m. is possible for some time, as shown by experiments in low pressure chambers and various Himalayan expeditions (3, 7, 8, 9, 14, 17), but permanent settlements are found up to 5,000 m. only (Andes). Thus, we can conclude that the presence of manlike creatures on Mars belongs to the realm of fantasy, since the minimum oxygen pressure required for man is at the least 100 times larger than the O_2-pressure which may at best be present on Mars.

It was found in decompression chamber experiments that the vital minimum oxygen pressure of homoiothermic animals (monkeys, dogs, cats, rabbits, guinea pigs, rats, pigeons) corresponds to an altitude of 8,000 to 12,000 m., i.e., barely less than 50 mm. Hg (figure 2). Poikilothermic animals (reptiles, amphibians, fishes, worms, etc.) withstood pressures below 50 mm. Hg down to 5 mm. Hg and less (5, 6). We know that a number of animals of the lowest species can live

* In regard to Venus, H. Haber (personal communication) presumes that life in the form of a *biological aerosol* may exist in certain strata of the Venusian atmosphere, where the temperature conditions for the existence of life are fulfilled. Haber further thinks it possible that life attempts to gain a first foothold on planets within their atmospheres in the form of these biological aerosols. There, life becomes a major factor in the development of the chemical constitution of planetary atmospheres. As a consequence, the living matter alters gradually its chemical and thermal environment by changing the atmosphere's constitution, its absorptive qualities regarding solar energy, and its proper radiation, until life may finally succeed in developing explosively. According to this concept, life does not depend entirely on the chances of the creation of a suitable environment effected through inorganic processes on the surface and within the atmosphere of a planet; instead, life itself invades a planet and attempts to form an environment favorable for extensive development. In the light of this concept, Venus and Earth can be considered as presently being in different stages of development.

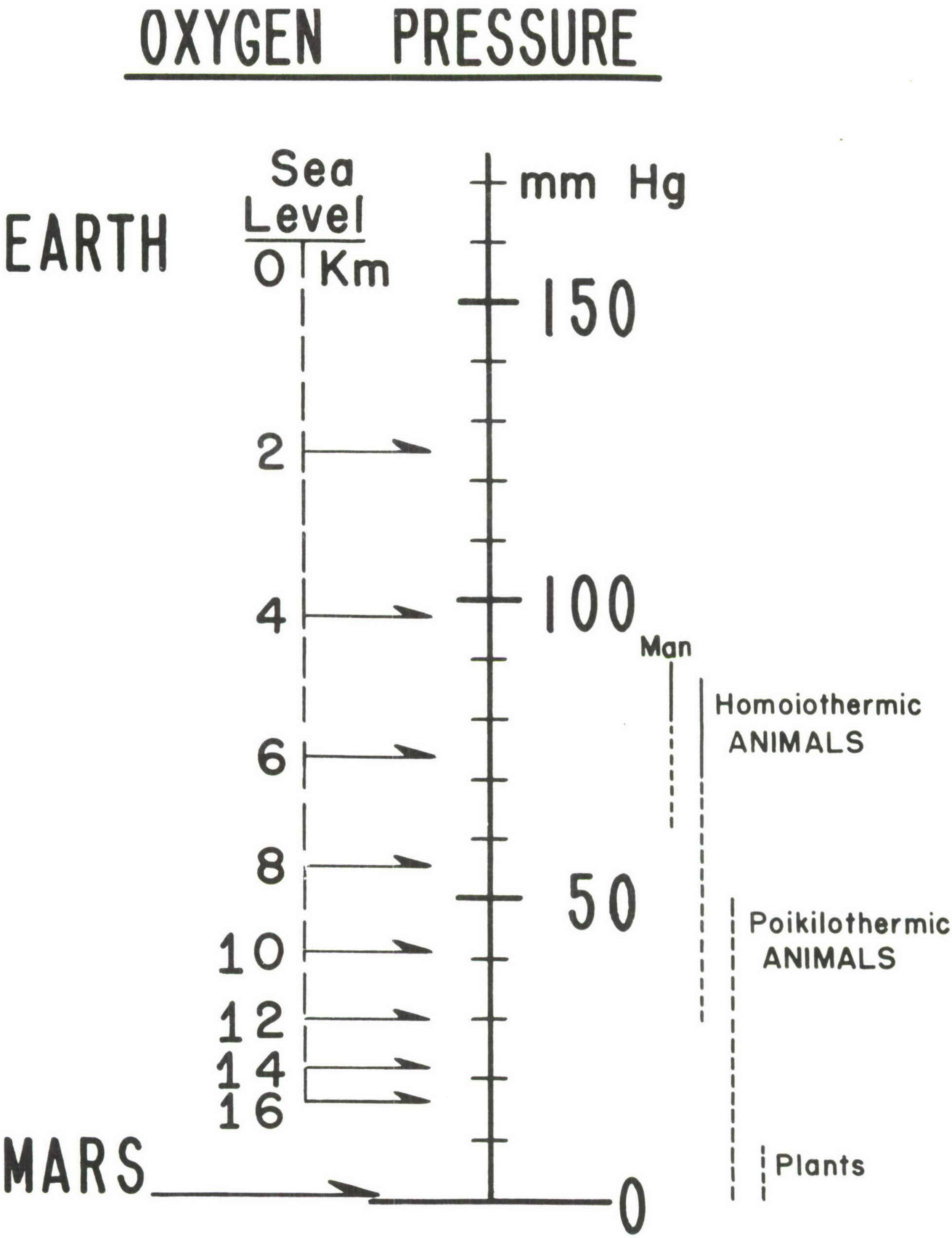

Figure 2

Left siae : Oxygen pressure on Earth and Mars.
Right side: Minimum oxygen pressure required for man, animals, and plants.

without oxygen for quite some time, e.g., in deep layers of stagnant lakes (19). Oxygen-free habitats are likely to develop in ice-covered ponds and lakes, if there is a high oxygen consumption by organisms. It is necessary that systematic investigations on the oxygen-pressure demand of poikilothermic animals be performed, since many of the experiments and observations made so far are only informative. Be that as it may, so far as the animal kingdom is concerned, the presence of homoiothermic and higher poikilothermic animals on Mars must be negated in view of the prevailing oxygen pressure. Arguing about the presence of lower species is futile because of the lack of clues to justify such an argumentation.

There are clues, however—namely, visible ones—that suggest the possible existence of vegetation on Mars. These clues are the seasonal discolorations of the green Martian areas (Lowell, 13) and the spectroscopic finding of Kuiper. Accepting this vegetation hypothesis, we are confronted with the problem of how to view it from the standpoint of physiology, since we must consider the apparent lack of oxygen in the Martian atmosphere.

It is true that plants also respire and require oxygen, though they are able to switch to anaerobic respiration at any time. There are plants which stop respiration as soon as the oxygen pressure of the air falls below 1.5 mm. Hg. This point is designated as the physiological zero point of plant respiration (10, 21). For growth and development, plants generally need a higher oxygen pressure. Notwithstanding, plants can overcome this difficulty by their ability to produce oxygen through the process of photosynthesis; in this respect, plants are superior to animals. They have their own oxygen generators in the chlorophyll-containing chloroplasts (20, 23). As is well known, photosynthesis requires carbon dioxide and water as raw materials, as well as light and a certain temperature (18). Do these factors reach or exceed the physiological minimum for the process of photosynthesis on Mars?

First of all, the temperature minimum for photosynthesis lies generally some degrees around the freezing point of water. Yet, in some arctic plants (lichens) a minimum of −20° C. has been observed. During daytime on Mars, these temperatures are exceeded by 20 to 40° C., according to W.W. Coblentz and C.O. Lampland (24).

Second, the minimum of light is certainly exceeded, since the solar constant on Mars averages 0.84 g cal/cm^2 min.

Third, the amount of carbon dioxide in the Martian atmosphere is, according to Kuiper, higher than that found in the terrestrial atmosphere.

Fourth, the presence of H_2O on Mars can be taken for granted. Still, the water question is possibly the weakest point in the combination of conditions for photosynthesis on Mars.

In short, if this last factor should not be definitely below the minimum (see J. Franck, 12), photosynthesis (as we know it) should be possible on Mars, since all other factors are adequate. Moreover, the combination of conditions for photosynthesis on Mars is, on the average, farther away from the optimum than is that on Earth. It is, therefore, improbable, that plants of higher order—such as vascular plants—can exist on Mars because of their higher demands as to temperature and humidity. Only lower plants which are very cold-resistant and drought-enduring (xerophytes) would be able to stand up against such climatic conditions. Kuiper's spectroscopic observations suggest the presence of lichens and mosses. Lichens and mosses belong to the two lowest subdivisions in the plant kingdom, the thallophytes and bryophytes. The lichens have some very peculiar characteristics. They consist of two dissimilar organisms, a fungus and a number of algae living in symbiosis. The fungal component offers protection from cold and supplies inorganic substances including water (because of the hygroscopic nature of most fungi). The algal component, in general the *Protococcus viridis*, builds up organic substances and supplies oxygen through photosynthesis. On account of this ideal symbiosis, lichens are very resistant to a dry and cold environment; they have hardly any demands as to the substratum upon which they live. We find them growing on barks of trees, and even on the surface of rocks and monuments. In the subarctic zones they represent the chief vegetation ("reindeer moss"). In the Himalayan mountains they can be found at altitudes up to 5,000 m. In short, they are the "last outposts" of plant life in every direction. They can exist on bare rocks because of their ability to decompose rock by producing organic acids. In this way, they are pioneer plants, preparing the humus for more demanding plants (16). In the course of the Earth's history they may well have made the first start for vegetation that developed on barren volcanic rocks. This phe-

nomenon can be observed, for instance, on the lava masses of the Sunset Crater in Arizona.

Liverworts, the more primitive types of the bryophytes, are almost as resistant as the lichens.

In fact, from the biological point of view, it is tempting to assume—even if there is no oxygen as on Mars, for instance—that plants similar to lichens and mosses may also be the last outpost of plant life and the pioneer plants on other planets.

Returning to terrestrial plants, we see that they have developed a mechanism which aids in the process of respiration and transpiration. This mechanism, when applied to an oxygen-and water-poor environment like that on Mars, affords a further support for the hypothesis of Martian vegetation. Being the center point of this treatise, this mechanism will be explained with the aid of some illustrations.

Figure 3 shows the microscopic section of the thallus of a lichen. We find an upper and a lower compact layer of dense mycelial threads, and a loose layer in between. The algal cells are scattered below the upper layer. The middle layer contains large air spaces.

Figure 4 shows a microscopic section through the thallus of a liverwort. We observe again combined intercellular air spaces forming a compartment with an outward-leading opening (stoma). In this discussion we are mainly interested in the air spaces and pores. Air spaces and pores have developed also in higher plants. Especially pronounced are these manifestations in the leaves of plants submersed in water. The system of intercellular air spaces is also called "aerenchyma." The maze of intercellular air passages is so widely spread that practically each cell of the parenchyma is in contact with the internal air. On account of this spongy structure, the inner surface of a leaf is much larger than the outer one. The ratio of inner to outer surface of leaves of different species (25) ranges between 10 and 30. The intercellular air spaces are in contact with the ambient air through the aforementioned pores or stomata. There are several hundreds of such pores per square millimeter of the upper or under leaf surface, respectively. Referring again to lichens, these plants are equipped mainly with primitive openings called "cyphellae." So much for the morphological aspect.

The physiological significance of this intercellular airing system is obvious. Not only is the area of exchange between leaf and environment increased enormously—a fact reminding us

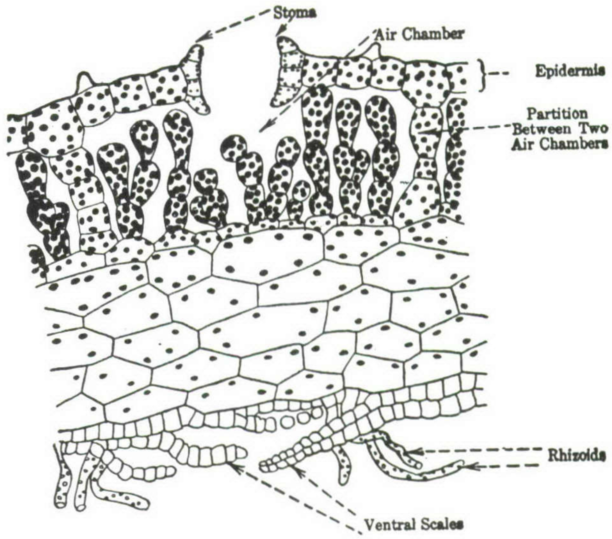

Figure 4

Cross section through a portion of the thallus of the liverwort *Marchantia*. Note in the air chambers the short filaments of cells, provided with numerous chloroplasts. (After R.M. Holman and W.W. Robbins, by permission of John Wiley and Sons, Inc., New York)

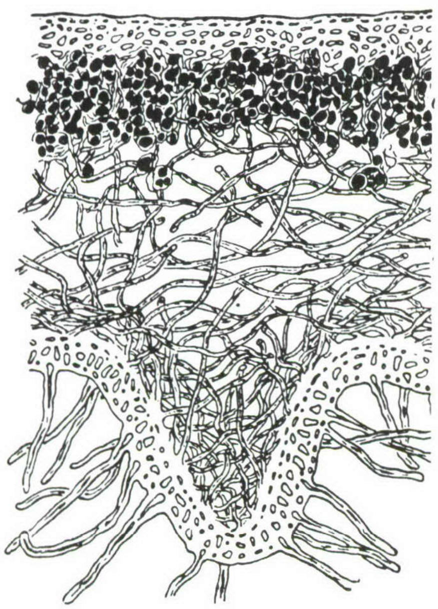

Figure 3

Cross section through the thallus of the lichen *Lobaria pulmonaria;* 200 times. (After Weiss from Tobler)

of the surface area of the pulmonary alveoli (=100 square meter)—there has also been created a kind of endo-atmosphere, or internal atmosphere. It is this "private atmosphere," not the ambient air, with which the parenchymal cells are in direct contact or in gas exchange. The microclimate with which the plants supply themselves is more apt to meet the requirements in regard to environmental conditions (for instance, water vapor and oxygen). Analyses of the intercellular air revealed that their oxygen content may amount to 30 to 60 volumes percent (18). Hence, the air space serves to store the surplus oxygen produced by photosynthesis. In this way the system of intercellular air spaces facilitates the existence of plants in an oxygen-poor or oxygen-free environment (submersed water plants). Suppose the micromorphological structure of the hypothetical Martian plants had developed according to similar principles, then the objection that can be advanced against the existence of vegetation in an oxygen-free Martian atmosphere would lose weight.

In this relation it seems appropriate to discuss another objection occasionally raised against the vegetation hypothesis, i.e., protection from radiation and desiccation. The terrestrial plants have developed a waxlike cuticula on the leaf surface exposed to light, as well as cutinization of the epidermal cells. Such developments are called "photomorphoses." It is a sound assumption that such adaptive processes may take place also on Mars, if there is no ozone, for instance, for protection from ultraviolet radiation.

Let us return to the possible facilitation of the oxygen problem by the spongy structure of the plant leaves, which one might call "aeromorphosis." In this respect the picture of the Martian plant life would be the following:

Active plant life on Mars could be possible only on that side of the planet exposed to sunlight, as soon as—after sunrise—the combination of environmental conditions within the internal atmosphere becomes adequate. After sunset the plants would return to a dormant state. Plant life would then be photorhythmic—without light, no active life.

Perhaps, during the Proterozoic era on Earth, the first primitive life was intermittent in a similar way. Today, the terrestrial plants have an oxygen reservoir of 1.2 billion tons, so they can continue breathing during the night. However, plants existing in an oxygen-free atmosphere, such as on Mars, are forced to live on the "current production" of oxygen. They consume the oxygen in "statu nascendi," or take it from the small stores of their microclimate. After sundown, the plants return to a state of latent life on account of the cold. In an oxygen-poor or oxygen-free milieu, the combination of dark plus cold seems to be more adequate from the physiological viewpoint than darkness plus higher temperatures. In the latter case plants can develop, in general, only if the ambient atmosphere—like that on the Earth—contains oxygen in amounts sufficient for respiration at night. Vegetation on Mars absolutely requires cold nights in view of the hypoxia—or better even, anoxia—existing on this planet.

From the physiological standpoint, therefore, the assumption of a Martian vegetation does not create insurmountable difficulties. This is particularly so if due consideration is given to the relativity of the physiological combination of environmental factors, as well as to morphological and functional adjustments of the living organisms to extreme environmental conditions, as are found in great variety in terrestrial biology. When considering these facts, the oxygen problem offers fewer difficulties than is frequently assumed. It is not oxygen, but carbon dioxide, that is the conditio sine qua non for vegetation.

In regard to Haber's hypothesis concerning the possibility of life in the Venusian atmosphere, the biological aerosol within the proper layers of the atmosphere of this planet also could benefit from a similar morphological structure that permits formation of an internal atmosphere by drawing oxygen from the ambient carbon dioxide through the process of photosynthesis.

The problem of the presence of oxygen in the Martian atmosphere might be formulated from the physiological point of view as follows:

Although from the aspect of astronomy Mars practically does not have any atmospheric oxygen, from the aspect of physiology there might be an oxygen layer within the vegetative substrate which, at adequate temperature and humidity, moves around the planet together with the sunlight.

In concluding this subject, I want to thank Dr. Heinz Haber for his advice in pertinent astronomical questions and for very informative discussions.

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STUDY ON SUBGRAVITY STATES

FRITZ HABER, Ph.D.
Department of Space Medicine

PROJECT NUMBER 21-34-003
REPORT NUMBER 1

Air University

USAF SCHOOL OF AVIATION MEDICINE
RANDOLPH FIELD, TEXAS
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STUDY ON SUBGRAVITY STATES

INTRODUCTION

The mechanical principles of zero and subgravity are given in various papers (1–4). The means for producing zero- and subgravity states have also been described elsewhere (2). It may be noted here that, for the purpose of producing such states, an acceleration a is superimposed on the acceleration g because of the earth's gravity.

The total acceleration $\frac{dv}{dt}$ of a body in a straight upward or downward motion is given by

$$\frac{dv}{dt} = a - g \qquad (1)$$

if the direction of positive speed v is upward, and a is the superimposed acceleration. It is convenient to express the acceleration a in terms of g by writing

$$a = n \cdot g \qquad (2)$$

thus transforming Eq. (1) into

$$\frac{dv}{dt} = n \cdot g - g = -(1-n) \cdot g$$

If n is equal to zero the gravity free state results, and if $o<n<1$ the subgravity state prevails. The solution of Eq. (2) is

$$v = v_o - (1-n) \cdot g \cdot t \qquad (3)$$

For $t = 0$, v equals the initial speed v_o. With increasing time v reaches the value zero.

$$v = o = v_o - (1-n) \cdot g \cdot t_o$$

$$t_o = \frac{v_o}{(1-n) \cdot g} \qquad (4)$$

After this time the speed becomes directed downward and reaches the value $-v_o$. The pertinent time is

$$t_d = \frac{2v_o}{(1-n) \cdot g} \qquad (5)$$

The elevation of the body as a function of time is the integral of Eq. (3) and is

$$h = v_o \cdot t - \frac{1-n}{2} \cdot g \cdot t^2 \qquad (6)$$

The height is zero for $t = 0$ and becomes zero again for

$$h = o = v_o \cdot t_d - \frac{1-n}{2} \cdot g \cdot t^2_d$$

$$t_d = \frac{2v_o}{(1-n)g}$$

which is identical to Eq. (5). This equation gives the duration t_d as a function of gravity and initial speed. For some purposes it is convenient to have the duration as a function of gravity and elevation. This is achieved by introducing Eq. (4) in Eq. (6) and obtaining

$$h = \frac{v_o^2}{2(1-n)\cdot g} \tag{7}$$

By this equation the speed v_o in Eq. (5) can be replaced by the elevation h yielding to

$$t_d = \sqrt{\frac{8}{(1-n)\cdot g}\cdot h} \tag{8}$$

Eqs. (5) and (8), giving the sought relation of elevation, gravity, initial speed, and height, are plotted in figure 1.

Values of speed and elevation in figure 1 are chosen as applicable to elevators. It is seen that the obtainable durations are rather short, especially for small gravities. Only an increase in speed and elevations would yield reasonable durations.

However, both speed and elevations are limited in an elevator. Thus the logical choice is an airplane, which is unlimited in elevation and can cope with high speeds. In principle, the same equations as above would be applied for the calculation of duration, because the superposition of a horizontal speed does not affect their validity. The only condition to be observed is that the horizontal speed should be constant. Moreover, it is important that the vertical acceleration is kept at a constant value by suitable control of thrust and lift.

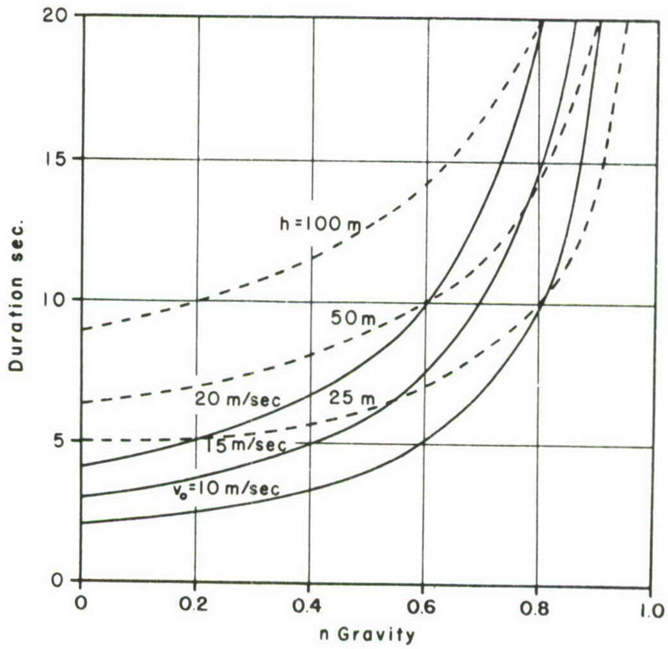


FIGURE 1

The duration of subgravity as obtainable in elevators.

These requirements could be fulfilled by measuring the acceleration in two directions. This can be accomplished by the installation of two accelerometers, one sensitive to vertical accelerations, the other sensitive to horizontal accelerations. However, one practical complication arises with this kind of instrumentation, because the flight path is not a straight but a curved line. To follow this line the airplane is forced to rotate slowly, so that its axis is always tangential to the flight path. The measurement of the acceleration should be independent of this rotation, thus requiring an orientation of the accelerometers relative to the direction of the earth's gravity. The only way to do this efficiently would be by the use of gyroscopes.

It is far more simple to mount the accelerometers in the airplane in a fixed position. One accelerometer measures acceleration in the longitudinal axis of the airplane, the other perpendicular to it. The different subgravity states are produced by keeping the longitudinal acceleration zero and the other acceleration at the desired gravity. In addition to its simplicity, this method still has another essential advantage over the aforementioned. As shown in figure 2, the direc-

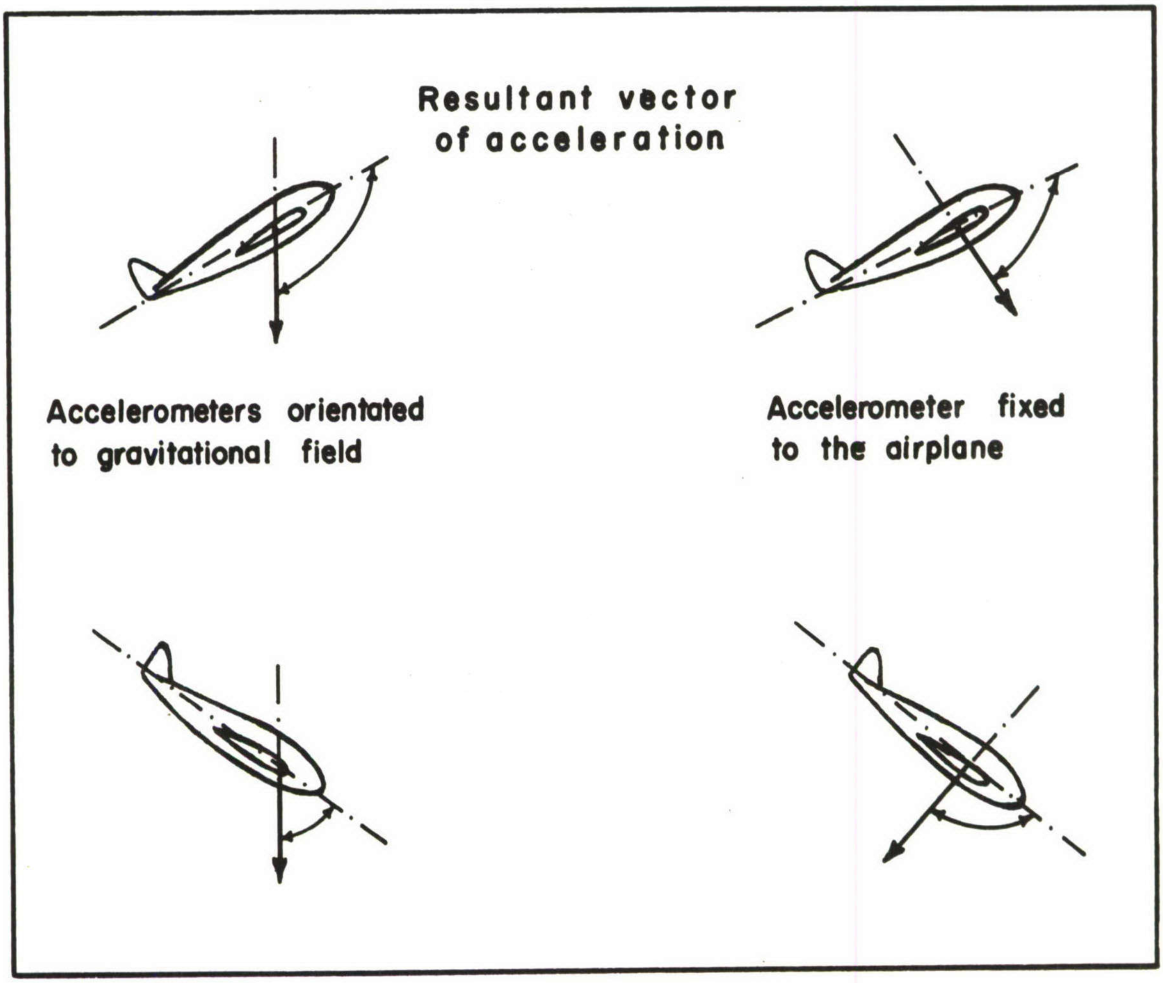
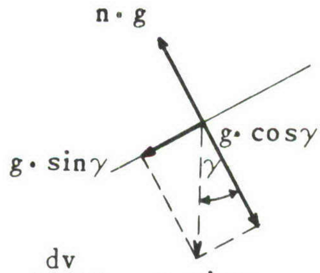


FIGURE 2

Acceleration vectors dependent of accelerometer installation.

tion of the vector of acceleration relative to the airplane depends on the position of the airplane, if the accelerometers are orientated relative to the earth's gravity. The vector slowly rotates relative to the airplane if the airplane rotates. This is avoided if the accelerometers are fixed to the airplane, thus virtually fixing the vector of acceleration also to the airframe. There is no difference in the two methods at zero gravity. The two methods differ mathematically by the fact that the first method uses the difference of the arithmetic values of the accelerations a and g, whereas the second considers the vectorial difference, because the superimposed acceleration a does not fall in the same line as g.

The above equations cannot be applied to the second method of producing subgravity. The total acceleration should be split into two components, one in longitudinal direction, the other perpendicular to it, thus yielding two equations.



$$\frac{dv}{dt} = -g \cdot \sin\gamma \tag{9}$$

$$v \cdot \frac{d\gamma}{dt} = -g \cdot \cos\gamma + n \cdot g \tag{10}$$

with γ denoting the angle of the flight path to the horizon. By transforming

$$\frac{dv}{dt} = \frac{dv}{d\gamma} \cdot \frac{d\gamma}{dt}$$

and dividing Eq. (9) by Eq. (10)

$$\frac{\frac{dv}{d\gamma}}{v} = \frac{-\sin\gamma}{-\cos\gamma + n} \tag{11}$$

is obtained. Eq. (11) can be converted to

$$\frac{dv}{v} = \frac{\sin\gamma}{\cos\gamma - n} \cdot d\gamma = -\frac{d(\cos\gamma - n)}{\cos\gamma - n} \tag{12}$$

This equation can be easily integrated

$$\ln v = -\ln(\cos\gamma - n) + \ln C.$$

Since for

$$\gamma = \gamma_0 \qquad v = v_0$$

finally

$$\frac{v}{v_0} = \frac{\cos\gamma_0 - n}{\cos\gamma - n} \tag{13}$$

Eq. (13) is suitable for calculating the minimum speed v_{min} at the peak of the flight path by setting $\gamma = 0$ i.e. $\cos\gamma = 1$
Thus

$$\frac{v_{min}}{v_0} = \frac{\cos\gamma_0 - n}{1-n} \tag{14}$$

This relation is shown in figure 3 in undimensional form and in figure 4 for an initial speed of 450 m.p.h. The value of the minimum speed is of practical interest, because this speed must not be allowed to drop below the stalling speed of the aircraft. Theoretically, it would be possible to obtain v = 0 in zerogravity flights because no lift is required and therefore no stall can occur. For reasons of a good maneuverability, however, it seems advisable to avoid these extreme values. A relation to determine the critical values can be found by the following consideration. The lift coefficient C_L at the minimum speed v_{min} is given by

$$C_L = \frac{n \cdot w}{\frac{\delta}{2} \cdot v^2_{min} \cdot S} \tag{15}$$

with w = weight of the airplane, δ = air density, S = wing area.
If $C_L \leqq 0.9$ is considered the margin value for stalling, Eq. (15) can be written

$$v^2_{Stall} \geq \frac{n \cdot w}{\frac{\delta}{2} \cdot S \cdot 0.9}$$

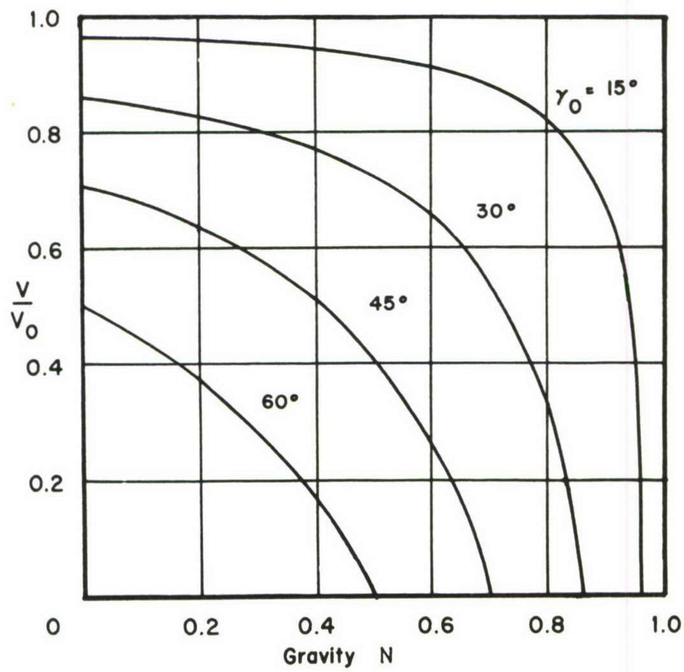


FIGURE 3

Minimum speed as function of gravity n for different initial angles γ_0 of climb.

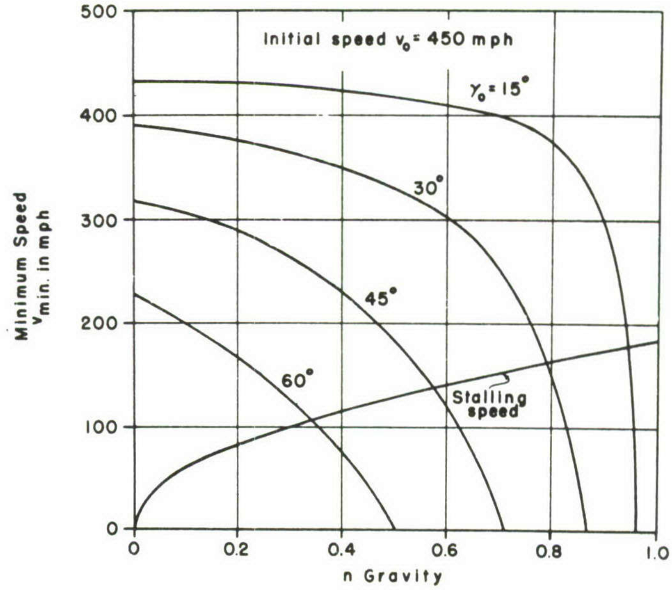


FIGURE 4

Minimum speed as function of gravity n for different initial angles of climb and an initial velocity of 450 m.p.h.

For an altitude of 10,000 feet and a wing loading of 55 lb./sq. ft., one arrives at

$$v_{Stall} \geqq 183 \cdot \sqrt{n} \quad [\text{mph}] \tag{16}$$

This relation is plotted into figure 4, thus dividing it into two fields. Only the combinations of gravity n and initial angle γ_o in the upper field avoid the stalling of the aircraft.

Returning to the calculation of the duration, it is necessary to transform Eq. (13) into

$$\sin\gamma = \pm\sqrt{1-\cos^2\gamma} = \pm\sqrt{1-\left[n+\frac{\cos\gamma_o - n}{\frac{v}{v_o}}\right]^2}$$

and to introduce into Eq. (9)

$$\frac{dv}{dt} = \mp g \cdot \sqrt{1-\left[n+\frac{\cos\gamma_o - n}{\frac{v}{v_o}}\right]^2} \tag{17}$$

It is convenient to convert into nondimensional form by introducing the variables

$$\phi = \frac{v}{v_o} \qquad \tau = \frac{g}{v_o} \cdot t$$

Finally the following differential equation or integral must be solved

$$\frac{d\phi}{d\tau} = \mp \frac{\sqrt{a + 2b\phi + c \cdot \phi^2}}{\phi} \tag{18}$$

$$\tau = \mp \int \frac{\phi \cdot d\phi}{\sqrt{a + 2b\phi + c\phi^2}} + C_2 \qquad (19)$$

with

$$a = -[\cos\gamma_0 - n]^2 \qquad b = -n[\cos\gamma_0 - n] \qquad c = 1 - n^2$$

The upper sign in the Eqs. (17), (18), (19), and (20) should be used for $\gamma > 0$, i.e., in the ascending leg of the flight path and vice versa. The solution is

$$\tau' = \mp \frac{1}{c}\sqrt{a + 2b\phi + c\phi^2} \pm \frac{b}{c \cdot \sqrt{c}} \cdot \ln\left[b + c \cdot \phi + \sqrt{c} \cdot \sqrt{a + 2b\phi + c\phi^2}\right] + C_2 \qquad (20)$$

The constant C_2 is determined by the condition

$$\tau = 0 \qquad \phi = 1$$

using the upper sign, since the point $\tau = 0$, $\phi = 1$ pertains to the ascending leg. The constant of the descending leg is determined by the condition that for $\phi = \phi_{min}$ both legs must have the same value τ. The minimum value ϕ_{min} can be calculated by $\frac{d\phi}{d\tau} = \frac{dv}{dt} = 0$ or from Eq. (18)

$$\sqrt{a + 2b\phi_{min} + c\phi^2_{min}} = 0$$

With this the argument of the logarithm reads

$$b + c \cdot \phi_{min} + \sqrt{c} \cdot \sqrt{a + 2b\phi_{min} + c\phi^2_{min}} = \sqrt{b^2 - a \cdot c}$$

Finally the following function is obtained

$$\tau = \frac{1}{c}\left[\sqrt{a + 2b + c} \mp \sqrt{a + 2b\phi + c\phi^2}\right] \pm \frac{b}{c \cdot \sqrt{c}} \ln \frac{b + c\phi + \sqrt{c} \cdot \sqrt{a + 2b\phi + c\phi^2}}{\sqrt{b^2 - a \cdot c}}$$

$$- \frac{b}{c \cdot \sqrt{c}} \ln \frac{b + c + \sqrt{c}\sqrt{a + 2b + c}}{\sqrt{b^2 - a \cdot c}} \qquad (21)$$

Eq. (21) is shown in figure 5 for v_o = 450 m.p.h. and two different gravities. The duration is obtained by setting $\phi = 1$ and using the lower sign

$$\tau_d = \frac{2}{c}\sqrt{a + 2b + c} - \frac{2b}{c \cdot \sqrt{c}} \ln \frac{b + c + \sqrt{c}\sqrt{a + 2b + c}}{\sqrt{b^2 - a \cdot c}}$$

By replacing a, b, c, and τ, the duration t_d is

$$t_d = \frac{v_o}{g}\left[\frac{2\sin\gamma_0}{1 - n^2} + \frac{2n(\cos\gamma_0 - n)}{(1 - n^2)\sqrt{1 - n^2}} \cdot \ln \frac{1 - n\cos\gamma_0 + \sqrt{1 - n^2} \cdot \sin\gamma_0}{\cos\gamma_0 - n}\right]$$

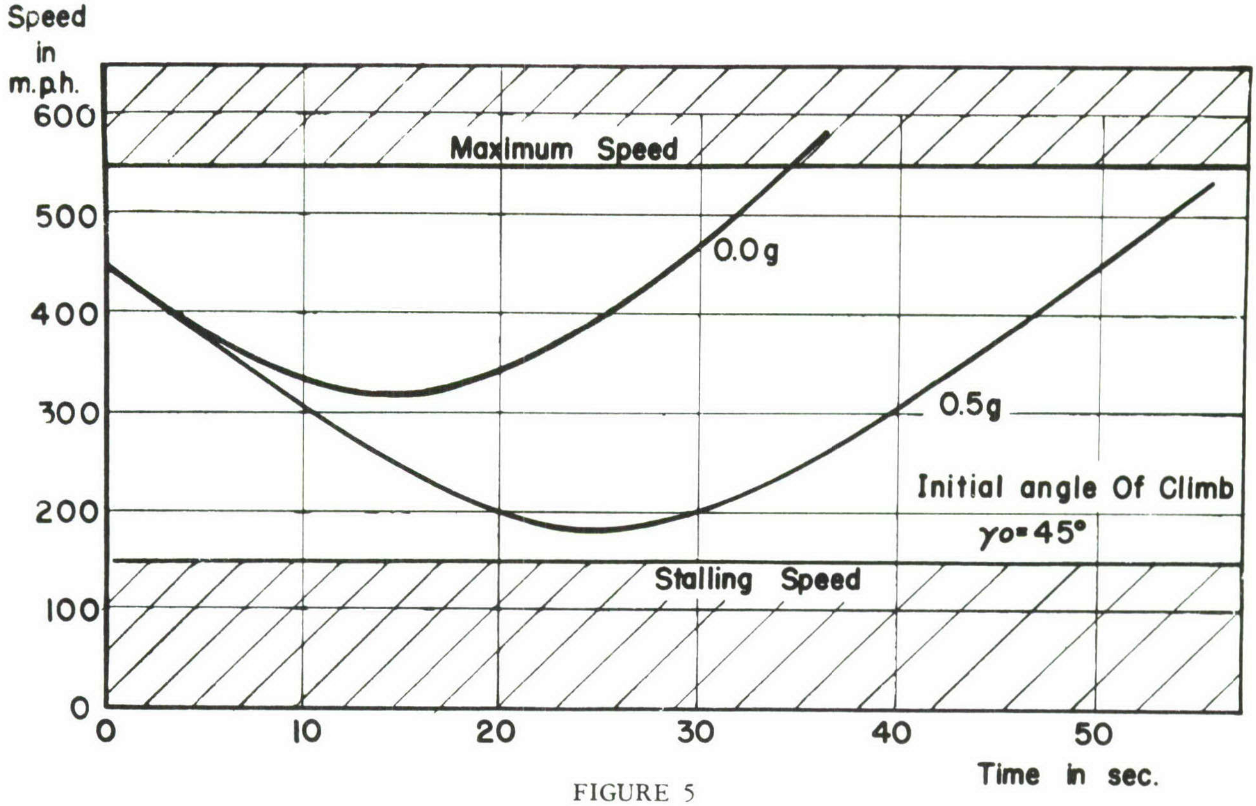


FIGURE 5

Speed as a function of time.

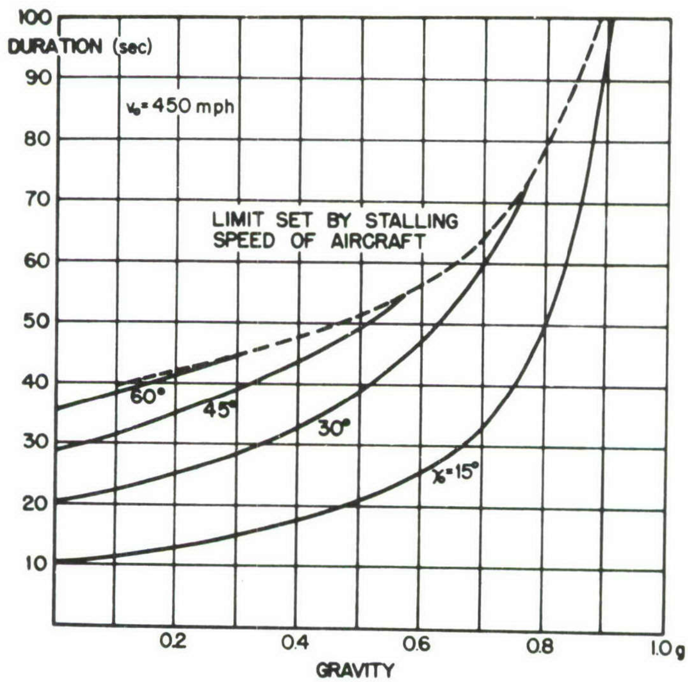


FIGURE 6

The duration of subgravity flights for various initial angles γ_0 of climb and an initial speed of 450 m.p.h.

Figure 6 shows the duration as given by Eq. (23) for an initial speed of 450 m.p.h. The limit set by the stalling speed is also plotted as furnished by figure 4.

Eq. (21) can be used for determining the shape of the flight path. This can be done numerically only, since $v = \frac{ds}{dt}$ cannot be eliminated from Eq. (21). A calculation has been made for an initial speed of 450 m.p.h. at an initial angle of climbing of 45° and for a gravity of n = 0.5.

For zerogravity n = 0 elimination and integration is possible yielding a parabola as flight path. For random gravities the flight path is not a parabola. Figure 7 shows the results.

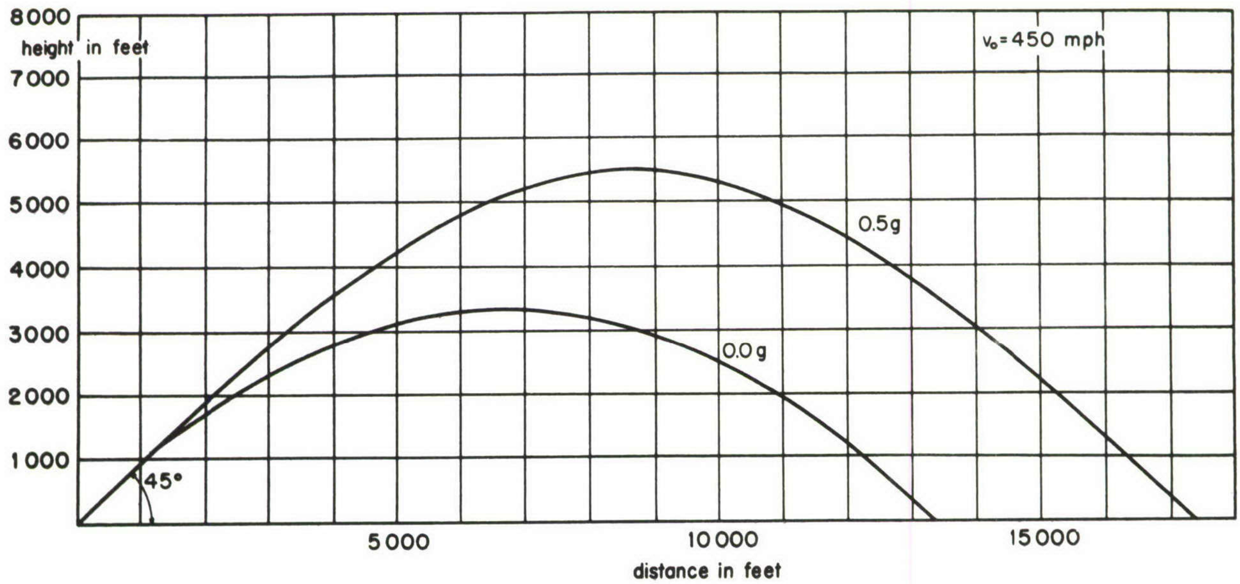


FIGURE 7

Two trajectories of subgravity flights.

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THE PHYSIOLOGICAL DAY-NIGHT CYCLE IN GLOBAL FLIGHTS

HUBERTUS STRUGHOLD, M.D., Ph.D.
Department of Space Medicine

SPECIAL REPORT

Air University
USAF SCHOOL OF AVIATION MEDICINE
RANDOLPH FIELD, TEXAS
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THE PHYSIOLOGICAL DAY-NIGHT CYCLE IN GLOBAL FLIGHTS

The planet Earth—during its revolution around the sun—rotates in 24 hours about its own axis. This rotation results in periodic changes in illumination, temperature, and other environmental factors affecting the entire globe. This external astronomical cycle with its two phases of day and night has imposed—directly or indirectly upon living beings in the course of their development—an internal physiological rhythm known by the term "physiological diurnal rhythm" or "physiological day-night rhythm or cycle." It is most impressively manifested by alternate phases of rest and activity, or by sleep and wakefulness. Rhythmic metabolic changes are the basis of this phenomenon. Respiration slows down during the night, as indicated by hypoventilation, lowered oxygen consumption, and increased alveolar carbon dioxide pressure (14). Thus, metabolism is decreased considerably, even below the experimental basal metabolism. A diurnal change of basal metabolic rate has been reported (1). There occurs a day-night cycle in the chemical constituents of the blood and in the activity of the liver, kidneys, and endocrine glands (10). Variations in cell mitosis have also been observed (6). All of these metabolic changes cause one to speak occasionally of a "metabolic clock." The most likely indicator of this metabolic clock is the body temperature (18). This temperature, in man, generally reaches a maximum in the late afternoon and a minimum in the early morning. During sleep the circulatory system shows a decrease in heart rate and blood pressure. A rise in the electrical skin resistance is a constant concomitant of sleep (17, 23). Activity of the intestinal tract is increased during sleep (3, 19). Generally, sympathetic nervous control prevails during the day, and the parasympathetic, during the night. This points to predominance of energy liberation during the day and of its restoration during the night. The somatic nervous system experiences a cycle of alertness and wakefulness in one extreme, and loss of consciousness, relaxation of the muscles, and disappearance of a number of reflexes in the other extreme. The electroencephalogram shows the characteristics of sleep in the amplitude, form, and frequency of the waves (16, 17).

From the standpoint of clinical pathology, it may be well to mention that certain symptoms of diseases (fever, epileptic fits, etc.) are predominant at certain hours of the day (2, 11).

The physiological cycle, as a kind of conditioned reflex (19, 20) synchronized with the astronomical event of day and night, is firmly established in man and in a number of the higher animals* (7, 8, 12, 13, 14, 15, 17, 21, 23, 24, 25, 27). This is demonstrated by three facts:

1. It is impossible to break this cycle over a longer period of time. For example: A dog, after being kept awake continuously for 14 days, died from severe degeneration of the ganglion cells. The effect upon mental and physical performance through the loss of 100 hours of sleep has been thoroughly investigated (9). It has been reported that a young man—for experimental purposes—stayed awake continuously for nearly 10 days to see whether sleep was "just a bad habit," and at the end of that time became so neurotic that the experiment had to be abandoned (4, 5).

2. The diurnal cycle can be lengthened or shortened to a limited degree only. The temperature cycle can be adjusted to an artificially produced 21- and 28-hour day but not to a 12- or 48-hour period (14).

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*Medical literature is so extensive in this field that references are confined to surveys and certain recent publications. The most comprehensive survey is offered in the book "Sleep and Wakefulness," by N. Kleitman (14).

3. A shift in the phases in the day-night cycle cannot be achieved instantly, but rather demands a certain amount of time for adjustment. With this last point, we arrive at our proper theme. This problem is not at all new. It is a familiar one in connection with shifts in factories, mines, and hospitals, in watches on ships (15), and in time-scheduling operations like the Berlin airlift (20). There is no question that it takes some time to become adapted to a new time schedule imposed professionally or socially.

And now, we are faced with a new type of shift of the physiological diurnal cycle imposed by traveling. The shift is caused by traveling with or against the rotation of the earth, there being a local time difference between the points of departure and arrival. The first practical experience was gained on sea voyages and by automobile and railroad travel over routes running parallel with the latitudes (14). In view of the low rate of speed of travel achieved by such means of transportation, the time difference amounts to little more than one hour per day. This may be uncomfortable, but it is insignificant physiologically. Yet, when we fly across the Atlantic in modern aircraft, crossing 100 meridians in less than a day, we obtain rather quickly, a shift of about a quarter of a day between the time on the continent of take-off and that on the continent of landing. We are adjusted to the local time of the continent of our take-off which—so to speak—has become our internal physiological time. Consequently, our physiological cycle fails to match—by 6 hours—the astronomical diurnal cycle on the other side of the ocean. According to my own observation—after two transatlantic flights in the fall of 1949 (from Washington, D.C., to Frankfurt, Germany, and return, after two months in Europe)—the most conspicuous manifestation was a shift in the time of sleep. The first night in Frankfurt, I did not fall asleep until 4:00 a.m. Mid-European Time (or 10:00 p.m. Eastern Standard Time) and woke up at 3:00 p.m. (or 9:00 a.m. Eastern Standard Time). I also observed a corresponding shift in my mealtime schedule. I have since interviewed a great number of people who had flown to Europe or to Japan and—after some time—back to the United States. Most of them very definitely experienced the time-shift effect. One individual (a physician) informed me that upon arrival from Europe to the United States—for four days—his body temperature maintained its maximum between 11:00 a.m. and 12 o'clock noon Central Standard Time, which corresponds to about 5:00 p.m. Mid-European Time. After five more days, his maximum body temperature had again returned to its normal period, about 5:00 p.m. Central Standard Time. This individual had developed a cold during the flight, which accounted for his interest in obtaining the range of his temperature.

Despite the necessity for a more precise study of the problem, it can be estimated that, after crossing the Atlantic or Pacific, it will take at least one week to become physiologically adapted to the day-night cycle of the new place.

This is demonstrated by the drawings presented in figures 1 and 2. The outer area of the square shows Greenwich or World time; the outer circle shows the local time; and the inner circle shows the physiological time. The darkened area indicates the night and the shaded area the normal time of sleep.

Figure 1 shows the time situation after a flight from the east coast of the United States to Europe and return. The picture on the left shows the physical and physiological cycle in Washington, D.C., or New York. The picture in the upper center shows the time change upon arrival after a flight to Europe (Mid-European Time zone). The physical day-night cycle has shifted; it has advanced 6 hours, while the physiological day-night cycle remains the same. After a stopover of about 10 days, it again coincides with the physical day-night cycle, as is shown in the picture at the right. The picture in the lower center and the one to the left demonstrates the behavior of the physical and physiological cycle after a trip from Europe to the east coast of the United States.

Figure 2 shows the corresponding physical and physiological time pattern of a trip from the East Coast of the United States to Japan or Australia; the time difference is about 10 hours.

For practical purposes, a time "dial board," constructed as shown in figure 3, may be useful.

The physiological phenomenon resulting from the discrepancy or noncoincidence between the geographical and physiological day-night cycle—after such global flights—can be designated as *geographic physiological phase shift in the day-night cycle,* or as *incomplete time or cycle adaptation.* During this incomplete physiological

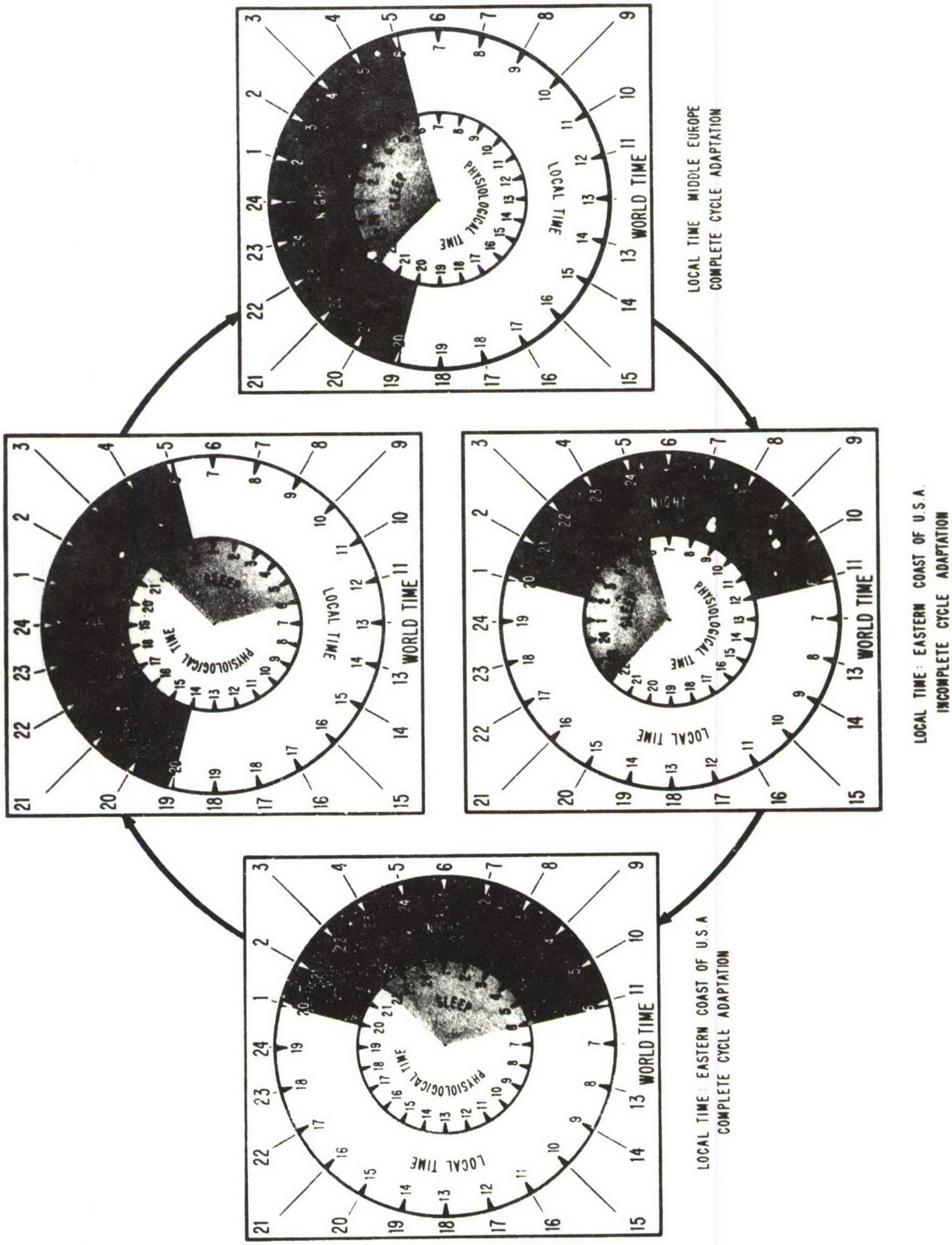

FIGURE 1

Phase shift between physical and physiological day-night cycle after a flight from the eastern coast of the United States to Europe and return.

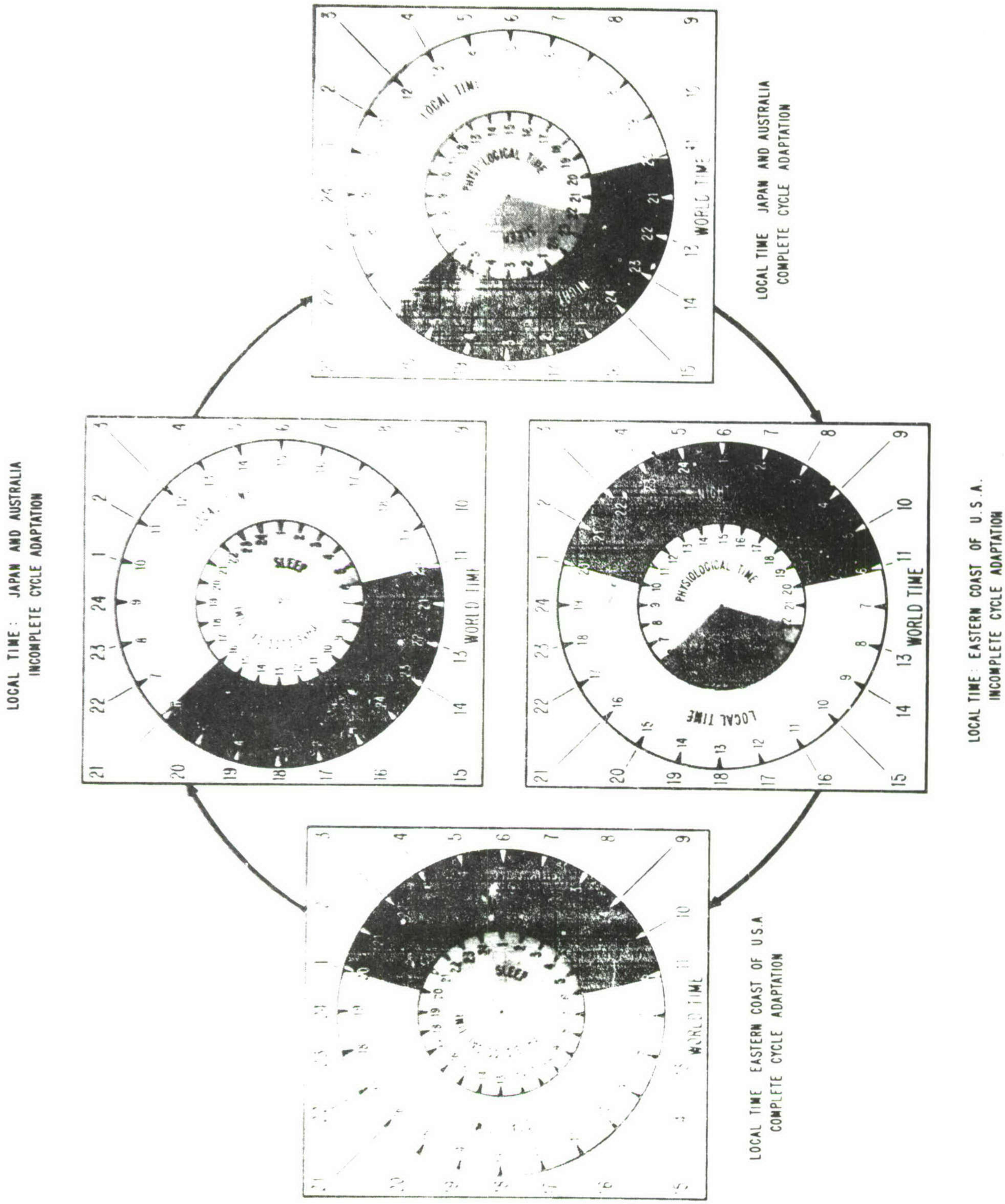

FIGURE 2

Phase shift between physical and physiological day-night cycle after a flight from the eastern coast of the United States to Japan or Australia and return.

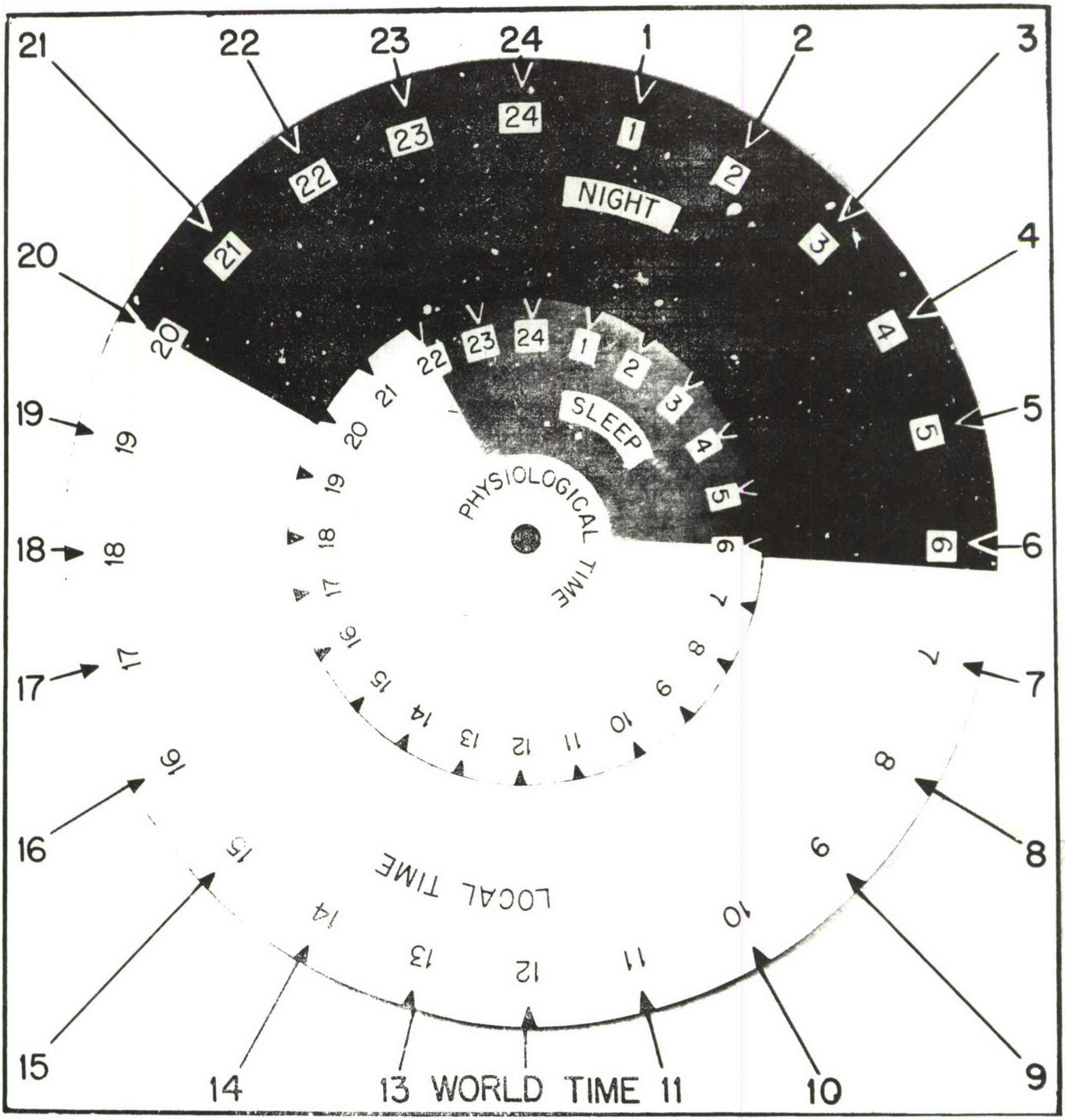

FIGURE 3

A time "dial board" to be used to demonstrate the time difference between World time, local time, and physiological time.

time adaptation, the newcomer's physiological cycle, or "metabolic clock," behaves as though he were still on the continent he just left. A number of days will pass before he has adapted himself physiologically to the local time of the new place. The time cycle distortion is then corrected; the phases are realigned.

So much for the physiological side of the problem. Now let us turn to the geographical and aeronautical side of the picture and take a look into the future. The geographical time shift is 4 minutes per meridian, or 15 meridians per hour. The route from San Francisco to Tokyo covers 100 meridians, a time difference equivalent to about 7 hours. The flight from New York to the most important landing places in Europe passes 80 to 100 meridians, corresponding to a time difference of 5 to 6 hours. A time difference of 5 to 8 hours can be gained, with present-day planes, within one day for the most important flight routes between the 30th and 50th latitude on the northern hemisphers. With planes of the future traveling at 600 m.p.h., a time difference of 12 hours, corresponding to 180 meridians, within one day will become a matter of routine. In such instances we obtain a complete inversion of the cycle. This point may be designated as the "Physiological Time Inversion Point." Crossing this point, the time shift becomes smaller again.

The extent to which the physiological time factor will affect professional and business life can be seen in the following example:

If we fly in the middle latitudes at the speed of daylight—a speed of about 700 miles per hour—leaving Paris for New York at 12 o'clock noon (lunch time), upon our arrival in New York after 5 hours of flight it would still be lunch time physiologically, even though our next meal would be the evening dinner.

Figure 4 shows the speeds at which daylight wanders around the globe at various latitudes. This diagram may serve as aid for the aforementioned example and similar ones. These examples may be sufficient to show the complexity of the physiological time factor in future flight: the less time-consuming, the more time-confusing. However, the principal features of this time complex are simple, and they are apparent in present-day flights.

It may be mentioned briefly at this point that global flights will also entail seasonal changes in a matter of hours. This is the case in flights along the longitudes from one hemisphere to the other, resulting in a physiological season shift effect.

Flying into subarctic and arctic regions represents a combined seasonal and day-night problem which certainly offers an interesting and fruitful field for cycle researchers.

With regard to comparative physiology, it is interesting to note that the flyways of the migratory birds go, by and large, across the latitudes (latitude migration). With few exceptions they cross no more than 60 meridians or four time zones.

The foregoing is only a brief outline of the entire problem. Despite the fact that detailed studies must be made in this field, we are justified in drawing certain conclusions with regard to the following points:

1. *Efficiency*

Our problem is important for troops flown overseas and sent to the battle front immediately after their arrival—as well as for the time appointed for meetings in the diplomatic, economic, and military fields. As a rule, during the first two or three days after flights that cross more than five time zones, meetings should not be scheduled in the mornings after eastbound flights, nor during the afternoons after westbound flights. Furthermore, this matter should be considered of importance for lecturers, actors, and participants in tournaments (chess, Olympic games, etc.) which require the highest mental and/or physical efficiency.

In the event space flight should some day become a reality, physiological time regulation will play an important role in the efficiency of the crew in the strange permanent semidarkness of space (5, 26).

2. *Medical Care of the Sick and Wounded (Especially Air Evacuees—the First Few Days After Arrival)*

A gliding adjustment of the timetable for eating, sleeping, and treatment is recommended. When taking the temperature, for diagnostic purposes, one must consider the possible incomplete adaptation to the new physical day-night cycle.

3. *Permissible Frequency of Change in Cycle*

Since any greater shift of the physiological diurnal cycle is no doubt accompained by distinct disturbances, crews of transoceanic airplanes should not be subjected to this change

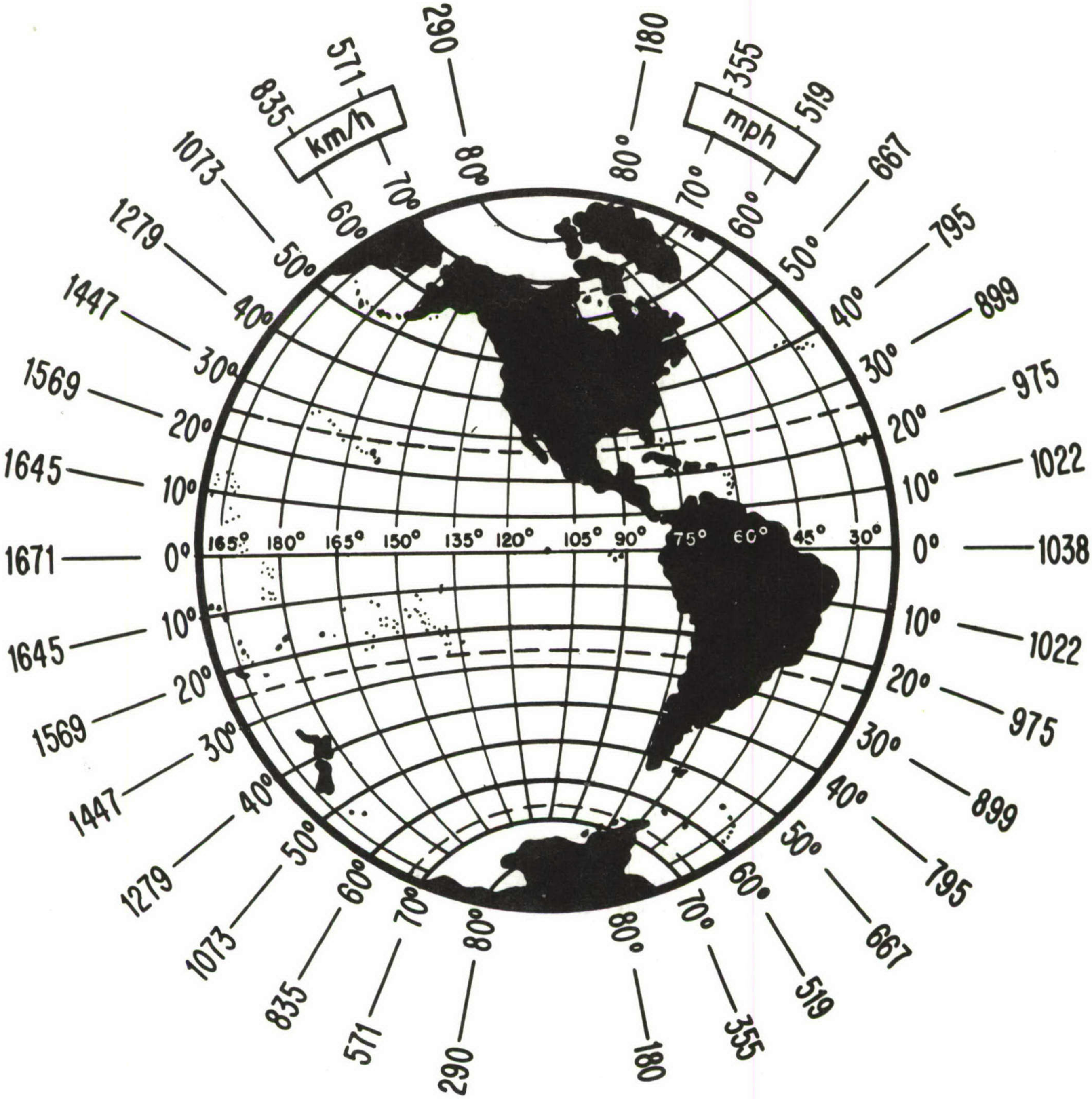

FIGURE 4

The speed at which daylight wanders around the globe at various latitudes expressed in miles per hour and kilometers per hour.

too often. If their stay on the other continent is for only a few days, they should maintain the diurnal cycle of their home continent. In the long run, frequent changes might result in neuroses. Certainly, some people are extremely sensitive; others can sleep at any time, at any place, and under any condition.

In studies concerning our problem, we can resort to the many experiments which have been

carried out in regard to shift work in factories and mines. Further research is necessary and should include studies of symptomatology, more accurate time pattern of symptoms, the time required for adaptation, facilitation of adaptation, prophylaxis, and medical advice. Observations should be concentrated on men and some of the higher animals like monkeys and birds. Valuable information could be gained in zoological gardens by observing animals brought in by air from different time zones. Most of the other animals like rats, cats, and rabbits are polyphasic, or better, polycyclic (14, 24, 25). This means that they show more than two phases of rest and activity during the 24-hour day. Infants, also, are polycyclic. Only older children and adults are monocyclic (14).

The diurnal cycle has been considered a problem of general medical and biological importance and interest, as is indicated by the existence of a special international society, and various national societies for the study of cycles or rhythms. This problem now demands specific consideration from the standpoint of fast air travel and the time has arrived for bringing it into focus.

In transportation by land and sea, the time shift remains at intracontinental and intraoceanic ranges; in modern transportation by air, it reaches the level of intercontinental and global dimensions.

The question may arise, "Is this a serious medical problem?" Certainly not! However, it has many implications and if questions arise in this respect—and they most certainly will—then aviation medicine should have the answer. The problem has nothing to do with the flight as such, nor does it represent an aftereffect of the flight. It merely represents a concomitant phenomenon induced by a speedy and long-range change of location in flights on a global scale.

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PHYSICS AND ENGINEERING OF RAPID DECOMPRESSION

A. General Theory of Rapid Decompression

FRITZ HABER, Ph.D.

Department of Space Medicine

HANS GEORG CLAMANN, M.D.

Department of Physiology and Biophysics

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Air University

USAF SCHOOL OF AVIATION MEDICINE
RANDOLPH FIELD, TEXAS
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A. GENERAL THEORY OF RAPID DECOMPRESSION

The physical process of rapid or explosive decompression has been the topic of discussion in many papers (1 - 4). The results in those papers were based on a number of assumptions and simplifications which, in many instances, are not fully justified. The object of this report is to arrive at a general theory of rapid decompression and to verify the theoretical results by experiments. Moreover, for practical use, a method will be presented to determine the important phenomena of rapid decompression.

DISCUSSION OF SIGNIFICANT FACTS

An attempt has been made to evolve a general theory of rapid decompression by taking into consideration many of the significant facts. No differentiation will be made between rapid decompression or explosive decompression since no factor has yet been found which really would justify the differentiation. In the following only the term <u>rapid decompression</u> will be used:

1. <u>Temperature</u>

Previous measurements have indicated that the temperature drop associated with rapid decompression can be very great. Temperature changes in the neighborhood of 100° C. have been observed (5). Therefore, to treat the process of decompression as an isothermal one is not justified. On the other hand, the process is not an adiabatic one because heat exchange between air and cabin wall is not negligible.

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2. Humidity

The influence of humidity on the physical process of decompression was shown in an earlier report (5).* Because the temperature drops below the dew-point in the first moments of decompression, the greatest part of the decompression will take place in air of 100 percent humidity regardless of the initial humidity. The heat released from condensing water vapor will also cause a deviation from an adiabatic process of an ideal gas. Therefore, the process should be treated as a polytropic one (i.e., a process that lies between an adiabatic one and an isothermal one).

3. Back Pressure

There is a difference between the rapid decompression that takes place in an aircraft and the rapid decompression that occurs in a usual experimental setup. In an aircraft the back pressure is equal to the atmospheric pressure of the ambient air and remains constant during the process of decompression. In experiments, however, two chambers of different size which can be connected are used. The smaller chamber simulates the cockpit of the aircraft cabin and has the same pressure as the cabin. The large chamber has a pressure which is lower than that in the small ohamber, thus simulating the pressure differences as they actually exist in the aircraft flying at high altitude. After suddenly opening the connection between the two chambers, the pressure in the larger chamber does not stay constant but rises, because of the airflow from the small chamber. It is this change in back pressure which makes an experimental decompression different from an actual case. Its significance should be considered. In the discussion that follows, p_{co} always stands for the pressure in the cabin or in the smaller

*In the cited reference, an error was unfortunately made concerning the sign in Eq. (2). This error has no bearing on the influence of the humidity as shown in figures 1 and 2 of the reference.

cnamber at the beginning of the rapid decompression, whereas p_{ao} stands for the pressure of the ambient air in the actual case, or for the pressure in the larger chamber before decompression, in an experiment.

4. Critical Pressure Ratios

There is a difference of flow pattern through the orifice depending upon the ratio $\frac{p_c}{p_a}$ of the two pressures on both sides of the orifice. If the pressure ratio increases, the velocity in the orifice also increases. In the true adiabatic case, the speed of sound is attained at a pressure ratio of 1.89 (1 - 4). This speed will not be exceeded even if the pressure ratio is increased more. The pressure ratio of 1.89 is therefore called the critical pressure ratio. Those ratios smaller than the critical are called subcritical and those ratios higher are called the supercritical ratios. In polytropic processes the ratio is smaller than 1.89.

5. Effective Cross Section

The practical flow of air through an orifice deviates from the theoretical flow. The reasons for such deviations are numerous, such as reduced velocity in the orifice due to friction or formation of eddies at sudden changes in cross section. All those modifications are usually accounted for by the introduction of an average coefficient of orifice, which depends upon the shape of the orifice. It is also possible to include pressure losses in ducts and bends in this coefficient. The coefficient of orifice thus reduces the geometrical cross section of the orifice to the so-called effective cross section.

In an experimental setup which includes all the above enumerated factors, it is possible to determine the thermodynamic process by measuring temperature and pressure. Knowing the nature of the thermodynamic process, it is then possible to draw conclusions concerning the aerodynamic facts of rapid decompression such as the pressure losses and the aerodynamic properties of the orifice.

Some of the basic concepts and all of the experimental results are discussed in this section. A full account of the theoretical deductions, however, is given in the appendix.

BASIC CONCEPTS

In an approximative fashion, the pressure change Δp* in terms of the initial pressure p_{co} can be written as follows:

$$\frac{\Delta p}{p_{co}} = \frac{\Delta V}{V_c} \tag{1}$$

ΔV being the volume of air which has passed through the orifice and V_c designating the volume of the cabin. The loss ΔV can be expressed by

$$\Delta V = A \cdot w \cdot \Delta t \tag{2}$$

if A is the area of the orifice, w the rate of flow in the orifice, and Δt the time element. Inserting Eq. (2) into Eq. (1) yields

$$\frac{\Delta p}{p_{co}} = \frac{A}{V_c} \cdot w \cdot \Delta t \tag{3}$$

The velocity w is a function of pressure and density. The density can be eliminated by introducing the speed of sound as a characteristic of the flow. The velocity w can thus be expressed by

$$w = c \cdot f\left(\frac{p_f}{p_{co}}\right) \tag{4}$$

c being the speed of sound, with f a function indicating the dependence of the rate of flow upon the final pressure p_f after decompression and the initial pressure p_{co}. It may be noted that the speed of sound is not necessarily attained as speed in the orifice. The numerical value of $f\left(\frac{p_f}{p_{co}}\right)$ is never greater

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*Δp, ΔV, and Δt are used for infinitesimally small changes of pressure, volume, and time.

than 1.0, indicating that the speed w never exceeds the speed of sound. With Eq. (4) in Eq. (3)

$$\frac{\Delta p}{p_{co}} = \frac{A \cdot c}{V_c} \cdot f\left(\frac{p_f}{p_{co}}\right) \cdot \Delta t \tag{5}$$

is obtained. Since information is sought about the time required for a certain drop in pressure, Eq. (5) is solved for

$$\Delta t = \frac{V_c}{A \cdot c} \cdot \frac{\frac{\Delta p}{p_{co}}}{f\left(\frac{p_f}{p_{co}}\right)} . \tag{6}$$

Despite the readers' possible reluctance or antipathy against something expressed in mathematical terms, it is suggested that Eq. (6) be checked for the combination of units. Since both sides of an equation must have the same units, the right-hand side of Eq. (6) therefore should appear in units of time. The last term in Eq. (6), containing the pressure, obviously is without units because only pressure ratios are used. Hence, the term $\frac{V_c}{A \cdot c}$ must appear in units of time which in fact is the case and can be easily demonstrated by factoring out

$$\frac{V_c}{A \cdot c} \mathrel{\hat{=}} \frac{ft^3}{ft^2 \cdot ft/sec} = sec$$

Considering different cases of rapid decompression, with identical pressure ratios involved, the term $\frac{\frac{\Delta p}{p_{co}}}{f\left(\frac{p_f}{p_{co}}\right)}$ will assume the same numerical value. From Eq. (6) it becomes apparent that the time Δt is then solely determined by the factor $\frac{V_c}{A \cdot c}$ This factor sets the time scale of the rapid decompression. It includes all constants of the system under consideration and is independent of the pressure conditions.

It is suggested that this term $\frac{V_c}{A \cdot c}$ be given an identifying name and be called <u>time-constant</u> t_c. A small time-constant means a short time of decompression, i.e., a fast decompression and vice versa. For example, a cabin of 500 cu. ft. and an area A of 1 sq. ft., together with speed of sound of 1,130 ft./sec. (68° F.) would yield a time-constant of 0.442 sec.

The theory, including other considerations such as various volume ratios of chambers in experimental decompression, subcritical and supercritical pressure ratios, has been elaborated upon more thoroughly in the appendix. It is shown in the appendix, that the total time t_E of decompression can be expressed in a similar fashion as in Eq. (6). From Eq. (xix) in the appendix, the time t_E is

$$t_E = t_c \cdot P_1 \tag{7}$$

P_1 is a function of the cabin pressure p_{co} before decompression, and p_{ao} the pressure of the ambient air. The term P_1 is described in the appendix and given in figure 1 as a function of $\frac{p_{co} - p_{ao}}{p_{co}}$.

There is one important conclusion to be drawn from Eq. (7) and figure 1. The value of P_1 does not depend upon the absolute value of the pressure difference $p_{co} - p_{ao}$, but depends only upon the ratio of this difference to the initial pressure p_{co}. A pressure difference of 200 mm. Hg at an initial pressure of 600 mm. Hg will bring about the same time of decompression as a difference of 100 mm. Hg at 300 mm. initial pressure. Or, another example, a pressure difference of 100 mm. Hg at 200 mm. Hg initial pressure yields a longer time of decompression than a pressure difference of 100 mm. Hg at 600 mm. Hg. The relative reduction of the initial pressure is the most important factor and not the absolute reduction.

Thus, the determination of the time of decompression is not difficult. If, for instance, cabin pressure p_{co} = 600 mm. Hg, ambient pressure p_{ao} = 200 mm. Hg then $\frac{p_{co} - p_{ao}}{p_{co}} = \frac{600 - 200}{600} = \frac{400}{600} = 0.66$. The pertinent value of P_1 is found in figure 1 to be 2.10. If the time-constant is again 0.442 sec, then the decompression time is

$$t_E = 0.442 \cdot 2.10 = 0.93 \text{ sec.}$$

Figure 1 is strictly valid only for decompression with a constant back pressure. For decompression from a small chamber into a larger one, it would be necessary to

use a slightly different form of the function P_1, together with the same time-constant. It has been found, however, that the general function as shown in figure 1, is applicable if the final pressure p_f is used instead of the initial

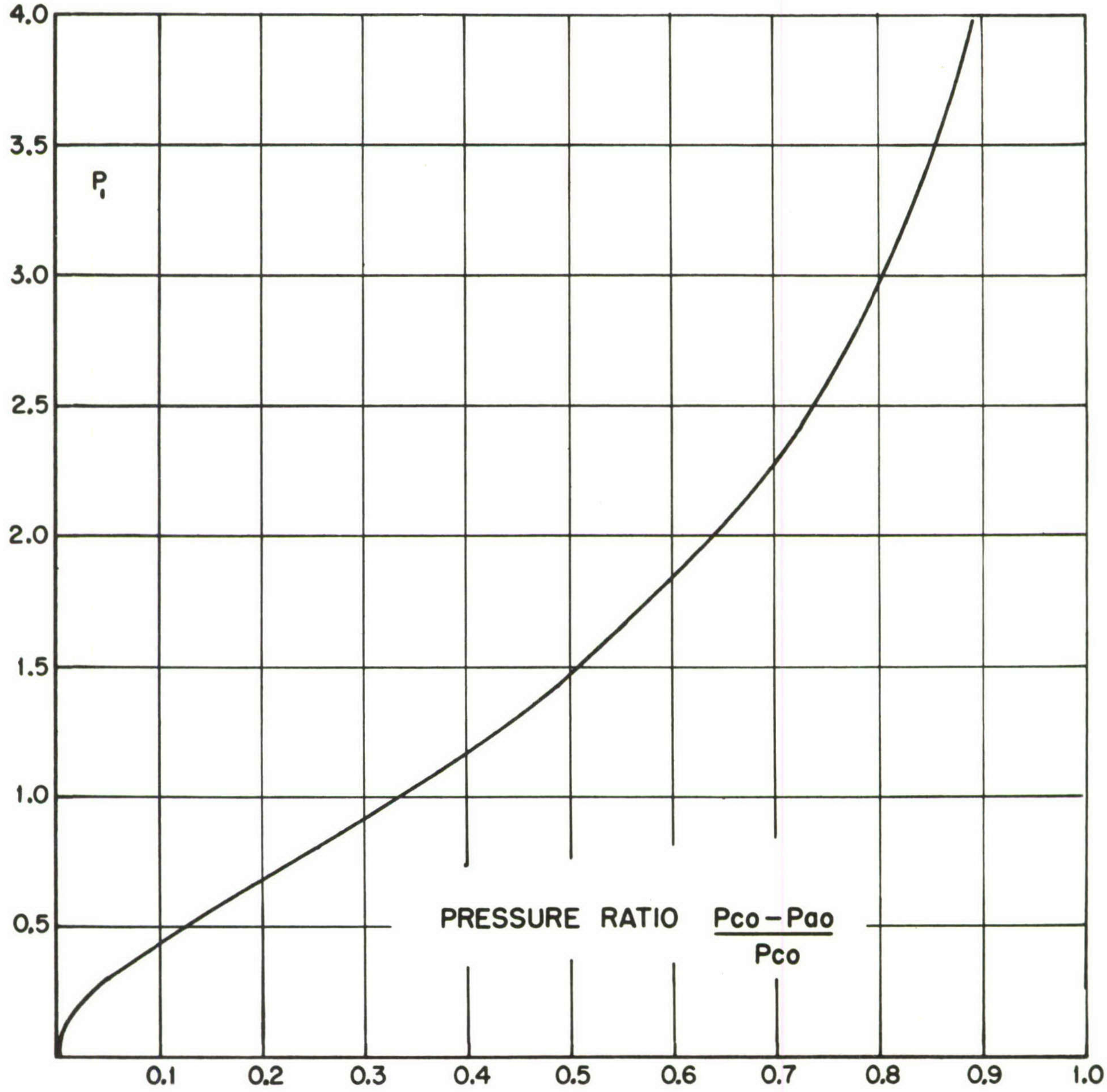

Figure 1

Pressure function P_1 for the total time t_E of decompression.

As shown in the text, the total time of decompression $t_E = t_c \cdot P_1$

pressure p_{ao}. The final pressure p_f is the pressure in both chambers after decompression and can easily be determined from the gas law to be

$$p_f = p_{ao} \frac{V_a}{V_a + V_c} + p_{co} \cdot \frac{V_c}{V_a + V_c} \qquad (8)$$

if V_a is the volume of the larger chamber and V_c the volume of the smaller one. The pressure difference to be used in figure 1 is then $p_{co} - p_f$ instead of $P_{co} - P_{ao}$ and is given by

$$p_{co} - p_f = (p_{co} - p_{ao}) \cdot \frac{V_a}{V_a + V_c} \qquad (9)$$

For all practical purposes this substitution is satisfactory with sufficient accuracy.

In order to arrive at a desired pressure difference $p_{co} - p_f$ it is necessary to evacuate the large chamber to the pressure p_{ao}, which is lower than the pressure p_f. Figure 2 shows a nomogram for calculation of the pressure difference $p_f - p_{ao}$ for various ratios $\frac{V_c}{V_a}$. The procedure for calculation is given in the legend of figure 2.

An evaluation of figure 1 is made for a time-constant of 1 sec. and is presented in figure 3. It shows the time of decompression in seconds as it depends on initial pressure p_{co} and ambient pressure p_{ao}. It also shows lines for constant pressure differentials $p_{co} - p_{ao}$. It may be noted that for a time-constant other than 1.0 the actual time of decompression changes accordingly. For example, a time-constant of .442 sec. and a time of decompression of 2 sec., as found in figure 3, would result in an actual time of decompression of 2 X .442 or .884 sec.

In many cases it is important to know the initial rate of the pressure change. As outlined in the appendix, this rate of pressure change can be determined as

$$\frac{dp_c}{dt} = - \frac{p_{co}}{t_c} \cdot P_2 \qquad (10)$$

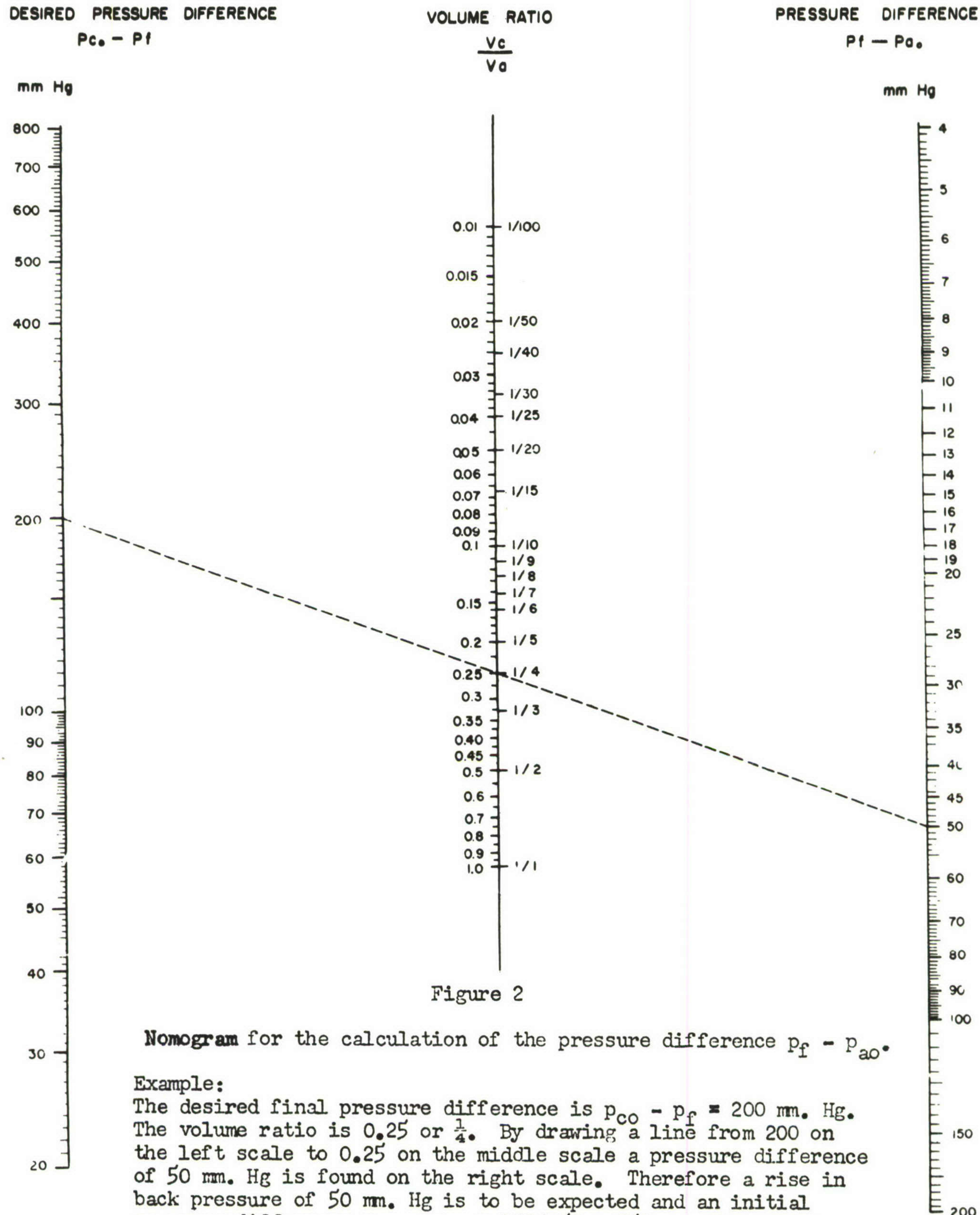

Figure 2

Nomogram for the calculation of the pressure difference $p_f - p_{ao}$.

Example:
The desired final pressure difference is $p_{co} - p_f = 200$ mm. Hg. The volume ratio is 0.25 or $\frac{1}{4}$. By drawing a line from 200 on the left scale to 0.25 on the middle scale a pressure difference of 50 mm. Hg is found on the right scale. Therefore a rise in back pressure of 50 mm. Hg is to be expected and an initial pressure difference $p_{co} - p_{ao} = 200 + 50 = 250$ mm. Hg would be chosen.

Eq. (10) shows that the initial pressure p_{co} and the time-constant t_c are the determining factors for the initial rate of pressure change. The term P_2 is again a function of the pressure difference $\frac{p_{co} - p_{ao}}{p_{co}}$ and is shown in figure 4. In the supercritical range, the term P_2 becomes constant because the speed in the orifice does not increase if the pressure ratio is increased. The determination of the rate of pressure change with the help of figure 4 is done in the following fashion: Assuming an initial pressure of $p_{co} = 600$ mm. Hg, ambient pressure 200, then $\frac{p_{co} - p_{ao}}{p_{co}} = 0.66$. From figure 4 P_2 is found to be 0.69. With a time-constant of 0.442 sec. the initial rate of pressure change is

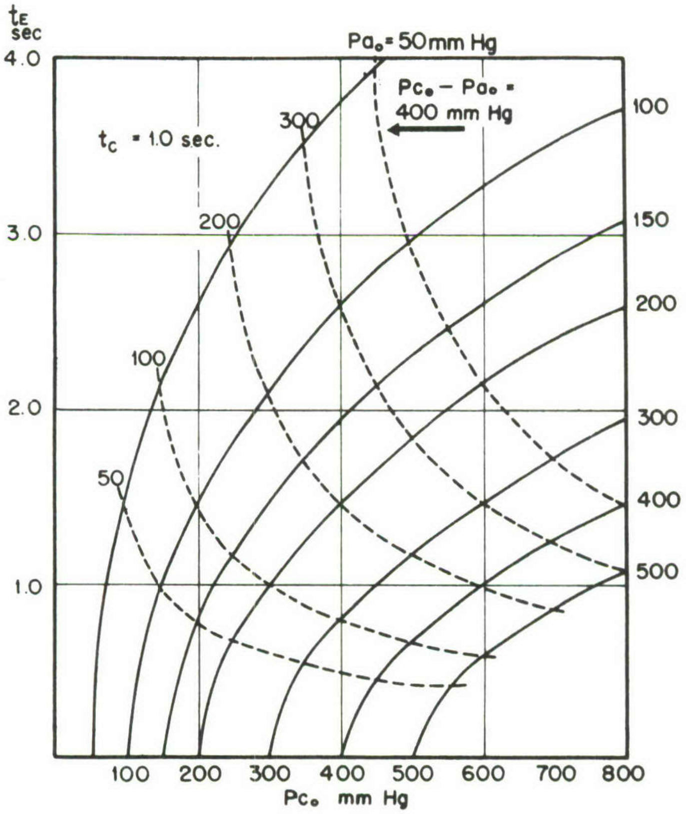

Figure 3

Total time t_E of decompression as a function of the initial pressure p_{co} for a time-constant $t_c = 1.0$ sec.

Note: Solid lines indicate ambient pressure p_{ao}; dotted lines indicate pressure differentials $p_{co} - p_{ao}$.

$$\frac{dp_c}{dt} = -\frac{600}{0.442} \cdot 0.69 = -937 \text{ mm Hg/sec}$$

An evaluation of figure 4 for a time-constant of 1 sec. is shown on figure 5. If the time-constant has a value other than 1.0 then the initial rate of pressure change varies accordingly. For instance, if a rate of change of 300 mm. Hg/sec. is found for the time-constant of 1.0 sec. the corresponding rate of change for a time-constant of 0.442 sec. would be

$$-300 \cdot \frac{1.0}{0.442} = -679 \text{ mm Hg/sec}$$

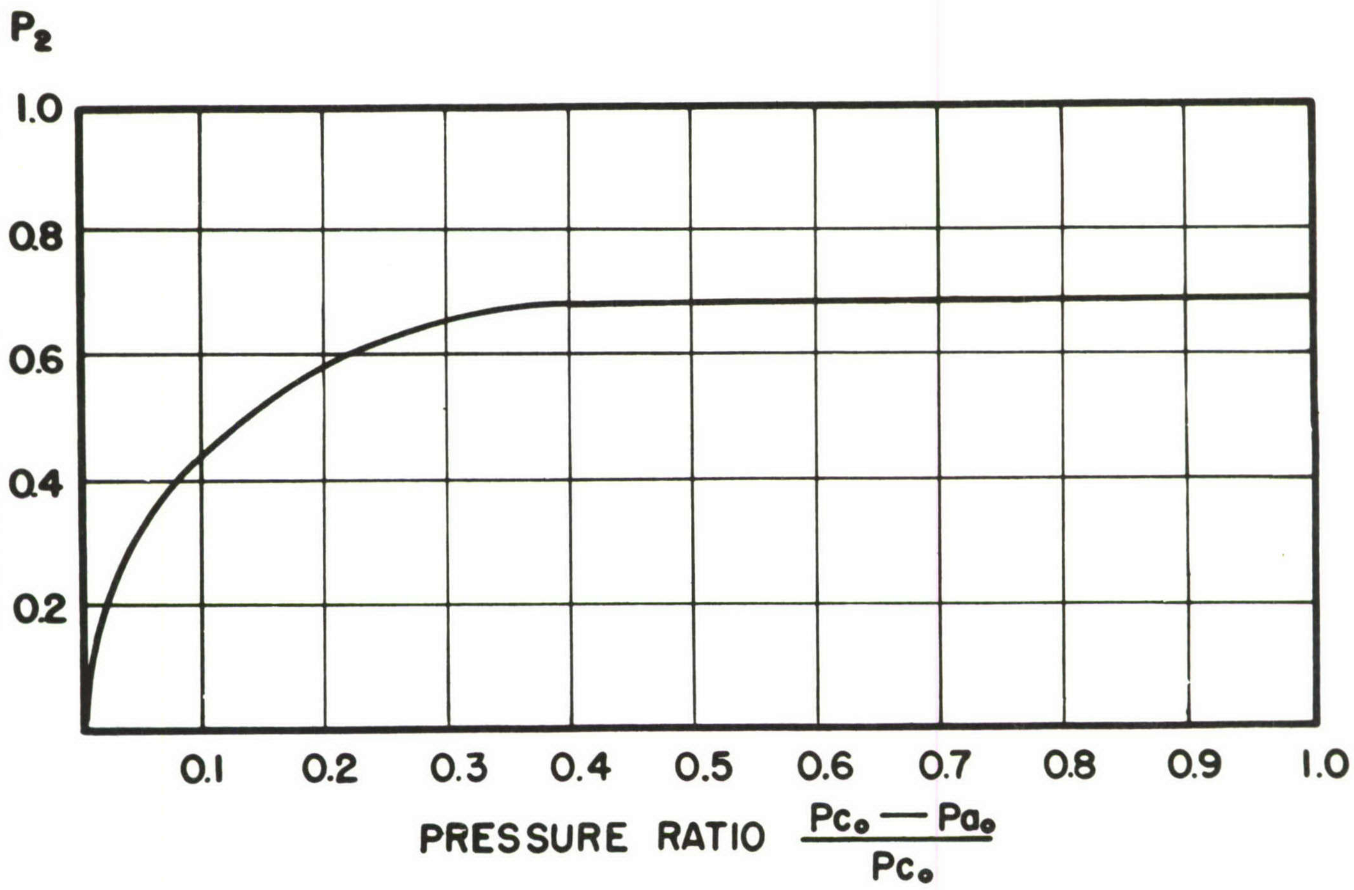

Figure 4

Pressure function P_2 for the initial rate of pressure change.

As shown in the text, the initial rate of pressure change is

$$\frac{dpc}{dt} = -\frac{P_{co}}{tc} \cdot P_2$$

The time of decompression, as used in the foregoing discussions, is determined by the fact that the cabin pressure p_c becomes equal to the ambient pressure p_a, i.e., after a complete equalization of pressures. This time is definite and becomes infinite only if decompression occurs in a complete vacuum. As can be seen from figure 3, this time of decompression can become very great and especially so if decompression to low ambient pressure is involved. In experimental decompression it is sometimes difficult to evaluate the recordings with regard to the decompression time because the pressure p_c approaches the ambient pressure p_a quite slowly. In order to facilitate the evaluation, it has been suggested that another time interval be used to characterize the process of decompression, rather than the total time. The method most often suggested is to

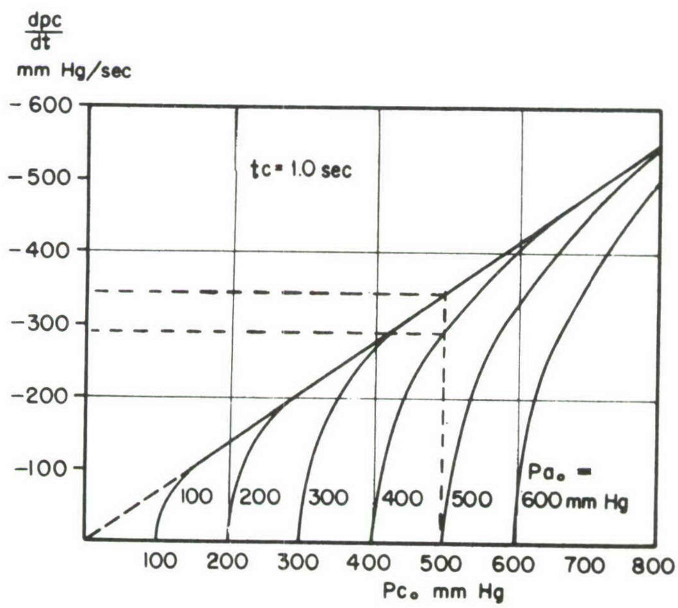

Figure 5

Initial rate of pressure change as function of the initial pressure for a time-constant t_c = 1.0 sec.
Example:
p_{co} = 500 mm. Hg, p_{ao} = 400 mm. Hg, $\frac{dpc}{dt}$ = -290 mm. Hg/sec.
For p_{co} = 500 mm. Hg, p_{ao} = 200 mm. Hg, $\frac{dpc}{dt}$ = -345 mm. Hg/sec.

measure the time which elapses until the initial pressure difference has been reduced to a certain fraction of its initial value. The introduction of this arbitrary fraction, however, is debatable.

It is therefore proposed that use be made of the initial rate of pressure change in order to arrive at a well-defined time which can be easily evaluated. For this purpose the initial rate is used as a constant rate throughout the rapid decompression. As shown on figure 6 the line of initial rate of change is extended until it intersects the ambient pressure p_{ao}. The point of intersection marks a time which is evidently related to the initial rate of pressure change and the pressure difference. As already mentioned, it has the additional advantage of convenient evaluation from recordings. This time may be called the constant rate time.

The constant rate time t_R is given by

$$t_R = t_c \cdot P_3$$

with P_3 being a function of $\frac{p_{co} - p_{ao}}{p_{co}}$ as shown in figure 7.

An evaluation of figure 7 for practical purposes is presented in figure 8 for a

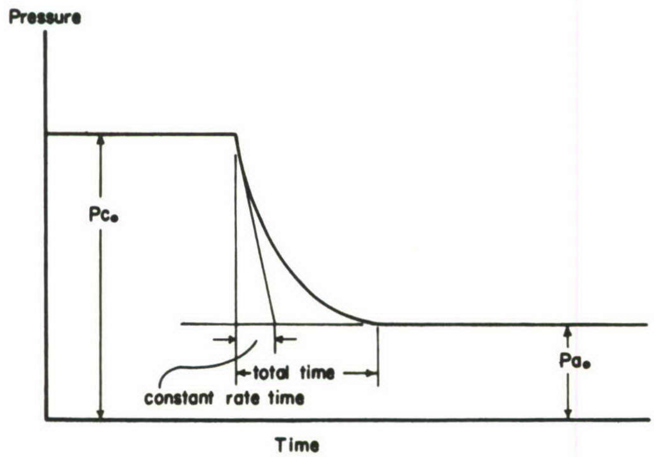

Figure 6

Definition of constant rate time t_R.

time-constant of 1.0 sec. It may be noted that for subcritical pressure ratios, the constant rate time is about half of the total decompression time.

Either the total or the constant rate time, or the initial rate of pressure change, can be used to determine factors which are inadvertently omitted in

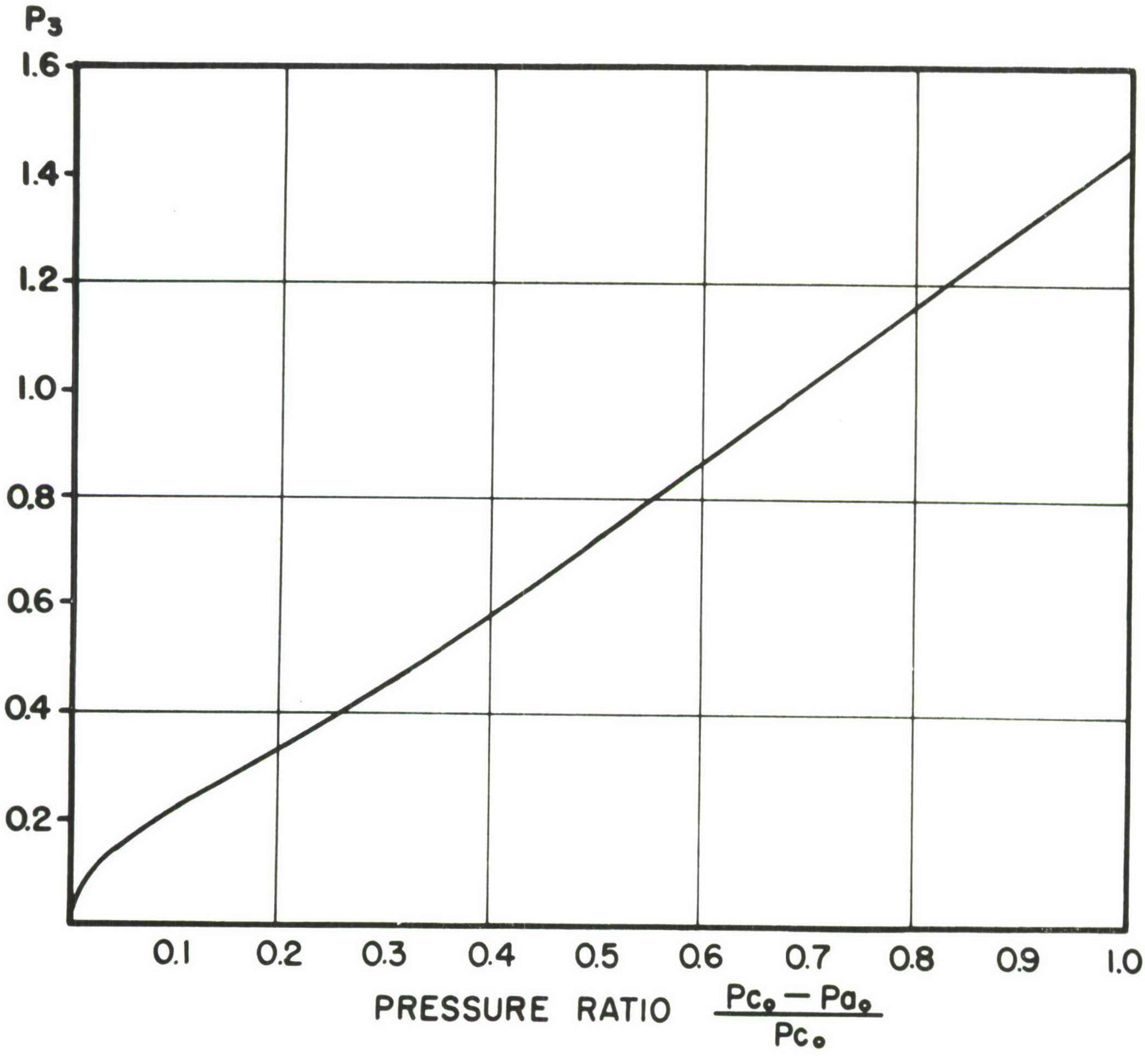

Figure 7

Pressure function P_3 for constant rate time t_R.

As shown in the text, the constant rate time $t_R = t_c \cdot P_3$

experiments or reports. For instance, it is possible to determine the time-constant if the pressures involved and the decompression time are known. The time-constant is then given by

$$t_c = \frac{t_E}{P_1}$$

On the other hand, it is possible to determine the pressure ratio involved if time-constant and decompression time are given. The general presentations of figures 1, 4, and 7 are best suited for such manipulations.

EXPERIMENTAL RESULTS

Experiments have been carried out in two different chamber arrangements at the USAF School of Aviation Medicine. The first one was of the so-called parasite type, i.e., a small, separate chamber with a duct connecting the small chamber with a large chamber. Three valves, which can be operated independently, allow

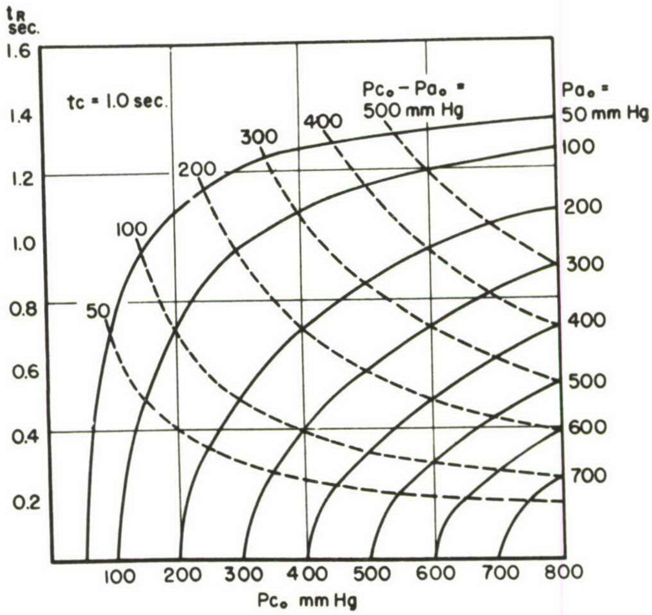

Figure 8

Constant rate time t_R as function of the initial pressure for a time-constant $t_c = 1.0$ sec.

the connection between the two chambers to be opened suddenly. A detailed description of this setup is given in a separate report (6).

The second chamber arrangement used in the experiments was a high-altitude chamber with a small air lock. The door from the air lock to the chamber has a circular opening of 11 inches in diameter. This opening can be sealed off by a membrane which is then punctured for the rapid decompression. This latter arrangement will be referred to as the D-chamber, in this report.

Measurements were taken of the absolute pressure p_c in the small chamber V_c and of the pressure difference $p_c - p_a$ between the small and the large chamber. For the pressure recordings Statham strain gages were used with a pressure range of 15 p.s.i. and a natural frequency of 100 c.p.s. The temperature changes in the small chamber were recorded with iron-constantan thermocouples. A very small time lag of the thermocouples was obtained by the use of a wire with 0.0008-inch diameter. The recordings were made with suitable galvanometers and a photokymograph. No amplification was necessary. A typical recording is shown in figure 9.

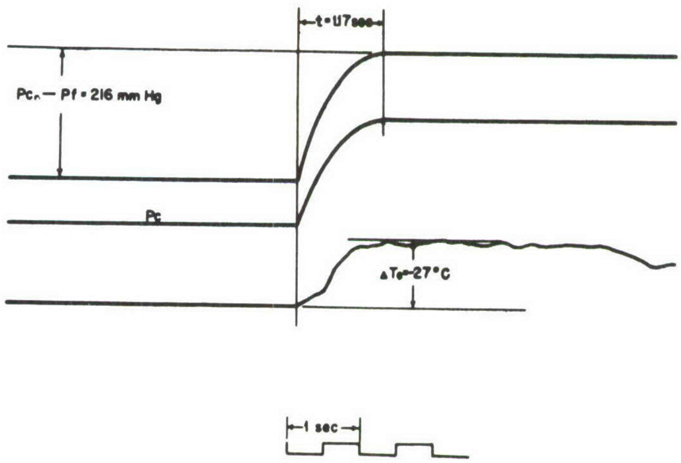

Figure 9

Recording of changes in pressure and temperature as they occurred during rapid decompression.

Note: The zero line for P_c is not given because there is insufficient room on the recording paper to show the entire range.

In all, about 75 rapid decompressions were recorded over a wide range of pressures, with various combinations of the aforementioned valves, in order to have various time-constants.

The recordings were first evaluated with regard to the pressure-temperature relationship. In polytropic processes the absolute temperature T and the pressure p are related by

$$\frac{T_f}{T_{co}} = \left(\frac{p_f}{p_{co}} \right)^{\frac{n-1}{n}}$$

where T_{co} is the absolute temperature before and T_f after decompression. n is the polytropic exponent. By plotting the temperature ratio $\frac{T_f}{T_{co}}$ against pressure ratio $\frac{p_f}{p_{co}}$ on double logarithmic paper, it is possible to determine the exponent $\frac{n-1}{n}$ from the slope and to find the polytropic exponent n. This has been done on figure 10. The least square slope indicates an exponent of $n = 1.16$, which is in the order expected, since the value should be between 1.0 (isothermal) and 1.4 (adiabatic). The value thus found was used to calculate the function P_1 as shown in figure 1.

It is realized that the polytropic exponent, as found in the described manner, actually is an average value over the time interval of the decompression rather

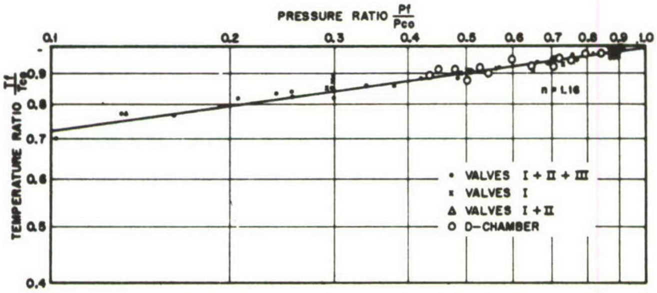

Figure 10

Pressure-temperature relationship in rapid decompression.

than an instantaneous one. However, in this discussion emphasis is on the average values, which are valid for the rapid decompression as a whole. The value of the polytropic exponent has an influence on the value of the speed of sound. With the experimentally found value $n = 1.16$ the speed of sound in ft./sec. is given by

$$c = 44.7 \cdot \sqrt{T_c + 459.4}$$

T_c being the temperature in °F of the air in the cabin. Figure 11 shows the speed of sound as a function of cabin temperature. If high accuracy is not required, a value of 1,000 ft./sec. **is most suitable.** The polytropic exponent $n = 1.16$ yields a critical pressure ratio of 1.75. The pertinent value of $\frac{p_{co} - p_{ao}}{p_{co}}$ is then, $1 - \frac{1}{1.75} = 0.427$.

In evaluating the recordings of rapid decompression time, the procedure applied was as follows:

First, the time-constant of the system used was calculated, assuming a coefficient of orifice of 1.0. Then, the total time t_E of decompression was

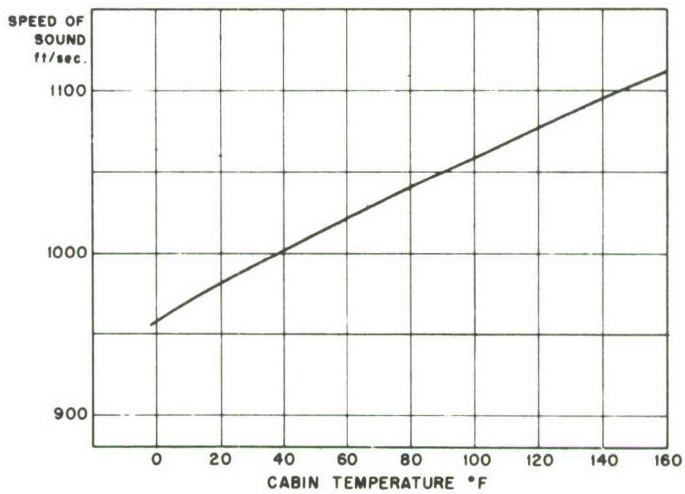

Figure 11

Speed of sound in rapid decompression as function of temperature.

measured from the pressure recordings, and the ratio $\frac{t_E}{t_c}$ calculated. These values were then plotted against the pressure term $\frac{p_{co} - p_f}{p_{co}}$. Figure 12 shows the results of all these experiments. Figure 12 also shows as a dotted line the theoretical values. It can be seen that the experimental values deviate from the theoretical ones, indicating that the effective cross section in the orifice differs from the geometrical one -- as used for calculating the time-constant. The deviation varies for the two different chambers which were used for the experiments. However, so far as the general trend is concerned, both the experiments and the theory are in good accord. This can be shown by taking into consideration a coefficient of orifice which compensates for the difference between geometrical and effective cross section. The agreement between theory and experiment is within reasonable limits if a coefficient of orifice of .25 is used for the parasite chamber and a coefficient of .95 for the D-chamber. See figure 13.

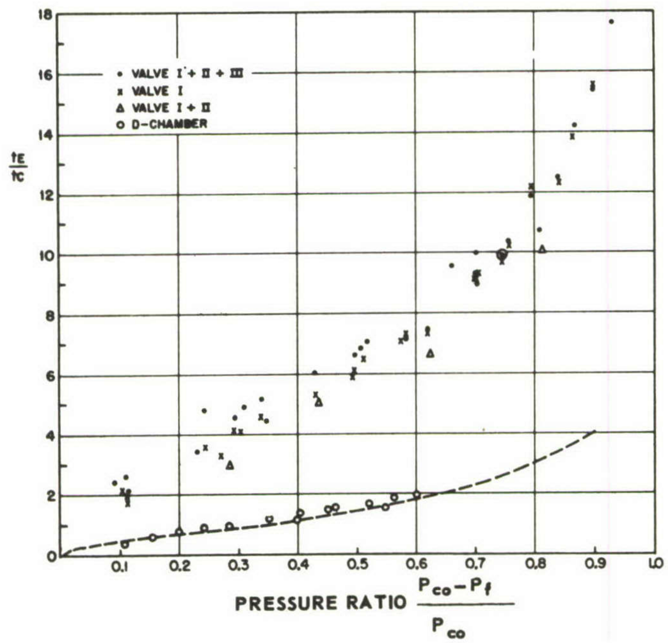

Figure 12

Ratio of $\frac{t_E}{t_c}$ resulting from experiments. Dotted line indicates theoretical values; the values of the D-chamber deviate slightly.

Assuming the thermodynamic considerations in the theory of rapid decompression are correct, it is possible to determine the coefficient of the orifice by computing the ratio of the theoretical value of decompression time to the experimental values of decompression time. The experimental results were evaluated in that manner and coefficients of .20 and .30 were found for the parasite chamber and coefficients of .90 to close to 1.0 were found for the lock chamber. The smaller coefficient of the orifice for the parasite chamber appears plausible considering the long ducts with sharp bends and sudden changes in diameter.

Taking into account the orifice coefficients as found in the experiments, the time constants for the various arrangements are as follows:

<u>Parasite Chamber</u>:

Valve I $\qquad t_c = 0.545$ sec.

Valves I and II $\qquad t_c = 0.272$ sec.

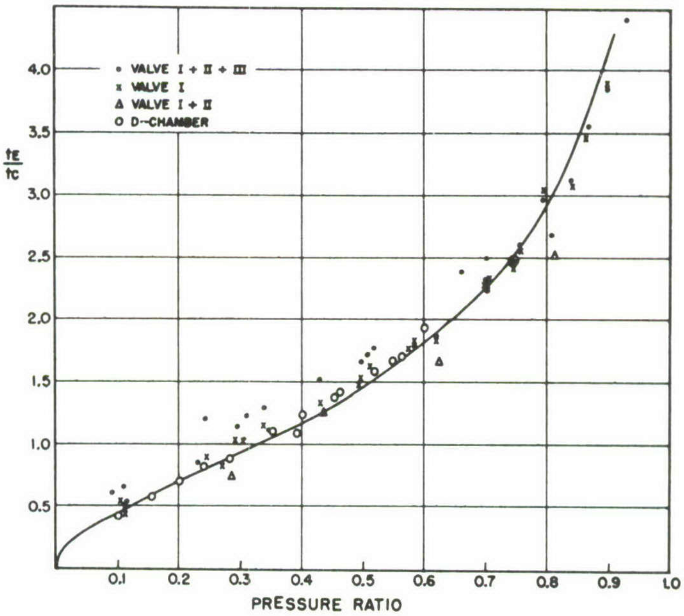

Figure 13

The results of decompression experiments presented as relationship between $\frac{t_E}{t_c}$ and $\frac{P_{co} - P_f}{P_{co}}$

All values are in good agreement with the theory (straight line) after being corrected for a proper coefficient of orifice.

Valves I, II, and III $t_c = 0.181$ sec.

D-Chamber: $t_c = 0.712$ sec.

It may be noted that the effective cross section is a point of uncertainty if it comes to reducing to practice the theory of rapid decompression since it has a strong influence on the time-constant. For cases like those occurring in aircraft, coefficients of 0.8 to 1.0 seem appropriate.

Acknowledgment

The authors wish to express their gratitude to Dr. R. W. Bancroft for his invaluable help and suggestions.

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APPENDIX

Notations:

p_c	Pressure in small chamber
p_{co}	Pressure in small chamber before decompression
ϱ_c	Air density in small chamber
ϱ_{co}	Air density in small chamber before decompression
V_c	Volume of small chamber
m_c	Air mass on V_c before decompression
p_a	Pressure in large chamber
p_{ao}	Pressure in large chamber before decompression
ϱ_a	Air density in large chamber
ϱ_{ao}	Air density in large chamber before decompression
V_a	Volume of large chamber
m_a	Air mass in V_a before decompression
p_f	Final pressure in both chambers after decompression
ϱ_A	Air density in orifice
A	Effective cross section of orifice
w	Speed of air in cross section of orifice
c_o	Speed of sound in V_c before decompression
n	Polytropic exponent
t	Time
t_c	Time constant $= \dfrac{V_c}{A \cdot co}$
t_E	Time of decompression
μ	Mass ratio $\dfrac{m_c}{m_a}$

The mass flow through the orifice is determined by

$$\frac{dm_c}{dt} = -\rho_A \cdot A \cdot w \tag{i}$$

The mass element is given by

$$dm_c = V_c \cdot d\rho_c \tag{ii}$$

In polytropic processes

$$\rho_c = \rho_{co} \cdot \left(\frac{p_c}{p_{co}}\right)^{1/n} \tag{iii}$$

$$d\rho_c = \frac{1}{n} \cdot \frac{\rho_{co}}{p_{co}} \cdot \left(\frac{p_c}{p_{co}}\right)^{\frac{1-n}{n}} \cdot dp_c \tag{iv}$$

For subcritical pressure ratios, i.e., $\frac{p_{co}}{p_{ao}} < 1.89$

the speed w is determined by

$$w = \sqrt{\frac{2}{n-1} \cdot n \cdot \frac{p_c}{\rho_c} \cdot \left[1 - \left(\frac{p_a}{p_c}\right)^{\frac{n-1}{n}}\right]} \tag{v}$$

Considering that the speed of sound is given by $c_o = \sqrt{n \cdot \frac{p_{co}}{\rho_{co}}}$

and introducing Eq. (ii) through (v) into (i) yields

$$\frac{d\left(\frac{p_c}{p_{co}}\right)}{dt} = -\frac{A \cdot c_o}{V_c} \cdot n \cdot \sqrt{\frac{2}{n-1}} \cdot \left(\frac{p_c}{p_{co}}\right)^{\frac{n-1}{n}} \cdot \left(\frac{p_a}{p_{co}}\right)^{1/n} \cdot \sqrt{\left(\frac{p_c}{p_{co}}\right)^{\frac{n-1}{n}} - \left(\frac{p_a}{p_{co}}\right)^{\frac{n-1}{n}}} \tag{vi}$$

The pressure p_a is constant, if the decompression takes place into the open air. However, if the air flows from one chamber to the other then p_a is not constant.

It is obvious that

$$dm_a = -dm_c \tag{vii}$$

or

$$V_a \cdot d\rho_a = -V_c \cdot d\rho_c$$

Integrating Eq. (vii) and introducing Eq. (iii) results in

$$\frac{p_a}{p_{co}} = \frac{p_{ao}}{p_{co}}\left[1 + \mu\left[1 - \left(\frac{p_c}{p_{co}}\right)^{1/n}\right]\right]^n \qquad \text{(viii)}$$

Finally

$$\frac{d\left(\frac{p_c}{p_{co}}\right)}{d\left(\frac{t}{t_c}\right)} = -n\cdot\sqrt{\frac{2}{n-1}}\cdot\left(\frac{p_{ao}}{p_{co}}\right)^{1/n}\left(\frac{p_c}{p_{co}}\right)^{\frac{n-1}{n}}\cdot\left[1+\mu\left[1-\left(\frac{p_c}{p_{co}}\right)^{1/n}\right]\right]\cdot\sqrt{\left(\frac{p_c}{p_{co}}\right)^{\frac{n-1}{n}}-\left(\frac{p_a}{p_{co}}\right)^{\frac{n-1}{n}}\left[1+\mu\left[1-\left(\frac{p_c}{p_{co}}\right)^{1/n}\right]\right]^{n-1}} \qquad \text{(ix)}$$

is obtained. To facilitate integration the following substitution is made

$$\frac{p_c}{p_{co}} = (1-\beta)^n$$

which is then expanded into a power series. It was found that accurary was still satisfactory if all terms of orders higher than β^2 were omitted. By this way Eq. (ix) is reduced to

$$\frac{d\beta}{d\left(\frac{t}{t_c}\right)} = \sqrt{\frac{2}{n-1}}\cdot\left(\frac{p_{ao}}{p_{co}}\right)^{1/n}\cdot\sqrt{a - b\cdot\beta - c\cdot\beta^2} \qquad \text{(x)}$$

with

$$a = 1 - \left(\frac{p_{ao}}{p_{co}}\right)^{\frac{n-1}{n}}$$

$$b = (n-1) - 2\left[1 - \frac{n+1}{2}\cdot\left(\frac{p_{ao}}{p_{co}}\right)^{\frac{n-1}{n}}\right]\cdot\mu$$

$$c = -\frac{1}{2}(n-1)(n-2) + 2(n-1)\cdot\mu - \left[1 - \frac{n}{2}(n+1)\cdot\left(\frac{p_{ao}}{p_{co}}\right)^{\frac{n-1}{n}}\right]\cdot\mu^2$$

Integration of (x) yields

$$\frac{1}{\sqrt{c}}\cdot\arcsin\frac{1+2\frac{c}{b}\cdot\beta}{\sqrt{1+4\frac{a\cdot c}{b^2}}} + C = \sqrt{\frac{2}{n-1}}\cdot\left(\frac{p_{ao}}{p_{co}}\right)^{1/n}\cdot\frac{t}{t_c} \qquad \text{(xi)}$$

C being the constant of integration, which is determined by setting

$$\beta = 0 \quad \text{for} \quad t = 0 \tag{xii}$$

The time t_E for decompression is found by setting $\frac{d\beta}{d(\frac{t}{t_c})} = 0$ in Eq. (x).

If $\frac{d\beta}{d(\frac{t}{t_c})} = 0$, then from (x)

$$\sqrt{a - b\cdot\beta - c\cdot\beta^2} = 0 \tag{xiii}$$

Taking into account the conditions (xii) and (xiii) the time t_E of decompression finally is obtained

$$t_E = t_c \cdot \sqrt{\frac{n-1}{2}} \cdot \frac{1}{\left(\frac{p_{a0}}{p_{c0}}\right)^{1/n} \cdot \sqrt{c}} \cdot \operatorname{arctg}\sqrt{4 \cdot \frac{a \cdot c}{b^2}} \tag{xiv}$$

This relation is valid for pressure ratios smaller than the critical. For greater ratios the speed in the orifice is independent of the back pressure p_a and is given by

$$w = \sqrt{2 \cdot \frac{n}{n+1} \cdot \frac{p_c}{\rho_c}} \tag{xv}$$

Introducing (xv) into Eq. (i) leads to

$$\frac{d\left(\frac{p_c}{p_{c0}}\right)}{d\left(\frac{t}{t_c}\right)} = -n \cdot \left(\frac{2}{n+1}\right)^{\frac{n+1}{2(n-1)}} \cdot \left(\frac{p_c}{p_{c0}}\right) \cdot \sqrt{\left(\frac{p_c}{p_{c0}}\right)^{\frac{n-1}{n}}} \tag{xvi}$$

which is easily integrated to be

$$t = t_c \cdot \frac{2}{n-1} \cdot \left(\frac{n+1}{2}\right)^{\frac{n+1}{2(n-1)}} \left[\frac{1}{\left(\frac{p_c}{p_{c0}}\right)^{\frac{n-1}{2n}}} - 1\right] \tag{xvii}$$

The supercritical flow exists until the pressure ratio $\frac{p_c}{p_a}$ has reached the critical value p_{cr}. During this supercritical phase the pressure p_a in V_a rises. When the critical ratio is approached the pressure p_c becomes

$$\frac{p_c}{p_{co}} = p_{cr}\cdot\frac{p_{ao}}{p_{co}}\cdot\left[\frac{1+\mu}{1+\mu\left(p_{cr}\cdot\frac{p_{ao}}{p_{co}}\right)^{1/n}}\right]^{n}$$

The time t_E' required for evacuation in the supercritical phase is then

$$t_E' = t_c\cdot\frac{2}{n-1}\cdot\left(p_{cr}\right)^{\frac{n+1}{2n}}\cdot\left[\left(\frac{1}{p_{cr}\cdot\frac{p_{ao}}{p_{co}}}\right)^{\frac{n-1}{2n}}\left[\frac{1+\mu\left(p_{cr}\cdot\frac{p_{ao}}{p_{co}}\right)^{1/n}}{1+\mu}\right]^{\frac{n-1}{2}}-1\right] \qquad \text{(xviii)}$$

For the following subcritical phase Eq. (xiv) becomes applicable. However, there is one fact to be considered. During the decompression in the supercritical phase, the temperature in V_c has dropped. It is therefore necessary to account for this in the computation of the factors a, b, c, and μ. The modified factors will be called a*, b*, c*, and μ* and are determined by

$$a^* = 1-\left(\frac{1}{p_{cr}}\right)^{\frac{n-1}{n}}$$

$$b^* = (n-1)-\left[2-(n+1)\cdot\left(\frac{1}{p_{cr}}\right)^{\frac{n-1}{n}}\right]\cdot\mu^{x}$$

$$c^* = -\frac{1}{2}(n-1)(n-2)+2(n-1)\cdot\mu^{x}-\left[1-\frac{1}{2}n(n+1)\left(\frac{1}{p_{cr}}\right)^{\frac{n-1}{n}}\right]\cdot\mu^{x}$$

$$\mu^* = \mu\cdot\left[p_{cr}\cdot\frac{p_{ao}}{p_{co}}\right]^{1/n}$$

It is also necessary to modify the value of the speed of sound from c_o to c_o^x in order to make possible the use of the same time constant for both phases. It is

$$c_o^x = c_o\left[p_{cr}\cdot\frac{p_{ao}}{p_{co}}\right]^{\frac{n-1}{2n}}\left[\frac{1+\mu}{1+\mu^x}\right]^{\frac{n-1}{2}}$$

The total time of decompression for an initial pressure ratio greater than the critical is then found to be

$$t_E = t_c\cdot\frac{2}{n-1}\cdot p_{cr}^{\frac{n+1}{2n}}\cdot\left[\left(\frac{1}{p_{cr}\cdot\frac{p_{ao}}{p_{co}}}\right)^{\frac{n-1}{2n}}\cdot\left(\frac{1+\mu}{1+\mu^x}\right)^{\frac{n-1}{2}}\cdot\left[1+\left(\frac{n-1}{2}\right)^{3/4}\cdot\frac{1}{p_{cr}^{\frac{n-1}{2n}}\cdot\sqrt{c^{x}}}\cdot\operatorname{arctg}\sqrt{4\frac{a^{x}\cdot c^{x}}{b^{x2}}-1}\right]\right] \qquad \text{(xix)}$$

Eq. (xix) can be written

$$t_E = t_c \cdot P_1$$

P_1 being a function of p_{co}, p_{ao} and μ. For $\mu = 0$ i.e. decompression into open air P_1 is given by

$$P_1 = \frac{2}{\kappa-1} \cdot (p_{cr})^{\frac{\kappa+1}{2\kappa}} \left[\left(\frac{1}{p_{cr} \cdot \frac{p_{ao}}{p_{co}}} \right)^{\frac{\kappa-1}{2\kappa}} \left[1 + \left(\frac{\kappa-1}{2} \right)^{3/2} \cdot \frac{1}{p_{cr}^{\frac{\kappa-1}{2\kappa}} \cdot \sqrt{c^x}} \cdot \operatorname{arctg} \sqrt{4 \frac{a^x \cdot c^x}{b^{x2}} - 1} \right] \right] \qquad \text{(xx)}$$

Eq. (xx) is plotted in figure 1 against the pressure difference $\frac{p_{co} - p_{ao}}{p_{ao}}$

In many cases, it is important to know the initial rate of pressure change. This rate can be determined by setting $\frac{p_c}{p_{co}} = 1.0$ in Eq. (ix) and Eq. (xvi). The initial rate of pressure change can then be expressed by

$$\frac{dp_c}{dt} = - \frac{p_{co}}{t_c} \cdot P_2$$

The term P_2 is in the subcritical range

$$P_2 = \kappa \cdot \sqrt{\frac{2}{\kappa-1}} \cdot \left(\frac{p_{ao}}{p_{co}} \right)^{1/\kappa} \cdot \sqrt{1 - \left(\frac{p_{ao}}{p_{co}} \right)^{\frac{\kappa-1}{\kappa}}} \qquad \text{(xxi)}$$

and in the supercritical range

$$P_2 = \kappa \cdot \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \qquad \text{(xxii)}$$

Figure 4 shows P_2 as a function of $\frac{p_{co} - p_{ao}}{p_{co}}$

The initial rate of pressure change can be used to determine the constant rate time t_R (see text). It is assumed that the initial rate is maintained throughout the entire decompression until the pressure p_c is equal to the pressure p_a. See figure 6. The initial rate time is then determined by

$$\frac{d\rho_c}{dt} = -\frac{\rho_{c0} - \rho_{a0}}{t_R}$$

that is

$$t_R = -\frac{\rho_{c0} - \rho_{a0}}{\frac{d\rho_c}{dt}} = t_c \cdot \frac{\rho_{c0} - \rho_{a0}}{\rho_{c0}} \cdot \frac{1}{P_2} = t_c \cdot P_3$$

with

$$P_3 = \frac{\rho_{c0} - \rho_{a0}}{\rho_{c0}} \cdot \frac{1}{P_2}$$

P_3 is shown in figure 7.

7

ESCAPE AND SURVIVAL AT HIGH ALTITUDE

FRITZ HABER, Ph.D.

Department of Space Medicine

PROJECT NUMBER 21-1207-0006

Air University

USAF SCHOOL OF AVIATION MEDICINE

RANDOLPH FIELD, TEXAS

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ESCAPE AND SURVIVAL AT HIGH ALTITUDE

The problem of bailout from an airplane was not too serious in the early days of aviation, but the development of fast and high-flying aircraft has changed the picture considerably. Because of the forces of windblast the pilot of today experiences difficulty in abandoning his disabled airplane, and after a successful escape he encounters the severe opening shock of his parachute.

As aircraft, because of competition and strategic necessities, are designed for even greater speed and higher altitudes, how will the problems of escape and survival be affected? Can any relief be expected, or will the stresses exceed the limits of human tolerance? There is no general answer. The answer depends on the specific problem.

For example, in the problem of escape proper, the windblast—and the resulting deceleration—will be the first consideration. In order that one can learn about the deceleration due to windblast in future flights, something must be known about the flying altitude and speed of the aircraft. Therefore, a plausible estimation of future aircraft performance will be made.

It is generally accepted that the aerodynamic heating of an airplane by friction establishes a limit for the attainable speed. This heating is a function of speed and heat transfer, the latter also being a function of speed and air density.

It is quite fortunate that the heat transfer depends upon air density in such a way as to be impaired by it. For this reason less heat is absorbed by the airplane at higher altitudes where the air is less dense. In other words, the smaller heat transfer permits a higher temperature of the air around the airplane; that is, it permits a higher speed. So far as temperatures are concerned, it is possible to fly faster at higher altitudes.

The permissible speed is obviously determined by the highest temperature which the airplane is permitted to assume. Since all metals tend to lose strength at high temperatures the final temperature should not exceed a value which would unduly affect the strength of the various parts of the airplane. For the purpose of showing the permissible speed at various altitudes, the skin temperature of the aircraft in this paper is limited to 250° C. Today, such a temperature is prohibitive with the designs of aircraft. On the other hand, higher skin temperatures are visualized for the future.

Figure 1 shows the permissible speed at various altitudes for skin temperature not to exceed 250° C. (480° F.).

So far it appears that aerodynamic heat poses no problem. It seems only necessary to fly higher in order to obtain greater speeds without overheating. Now the question arises if, aerodynamically, it is possible to fly under the conditions postulated by the thermal considerations.

The rarified air and resultant decreased drag at high altitudes allows an increase of velocity for a given thrust. In addition it is also necessary to fly fast for a definite aerodynamic reason. It is well known that an airplane needs a certain velocity for flying. This velocity creates the ram pressure which is essential for the conditions of proper airflow around the wing. What value of dynamic pressure is obtained if the thermal requirements are met (that is, if speed and altitude are as shown in figure 1)? Figure 2 shows the dynamic pressure under these conditions. At lower speed any dynamic pressure is feasible without danger of overheating. The higher the Mach number, however, the smaller the usable range becomes and the dynamic pressure becomes so low that standard wing loadings of today would require much too large a lift coefficient.

An airplane flying at 600 m.p.h. at sea level has a dynamic pressure of about 900 lb./sq. ft. Flying with the same speed at 30,000 feet produces a dynamic pressure of 300 lb./sq. ft. From figure 2 it becomes apparent that at higher speeds—e.g., those of Mach number 3—the dynamic pressures must be significantly smaller than those figures just quoted if the temperature of 250° C. is not to be exceeded. This indicates a falling trend in dynamic

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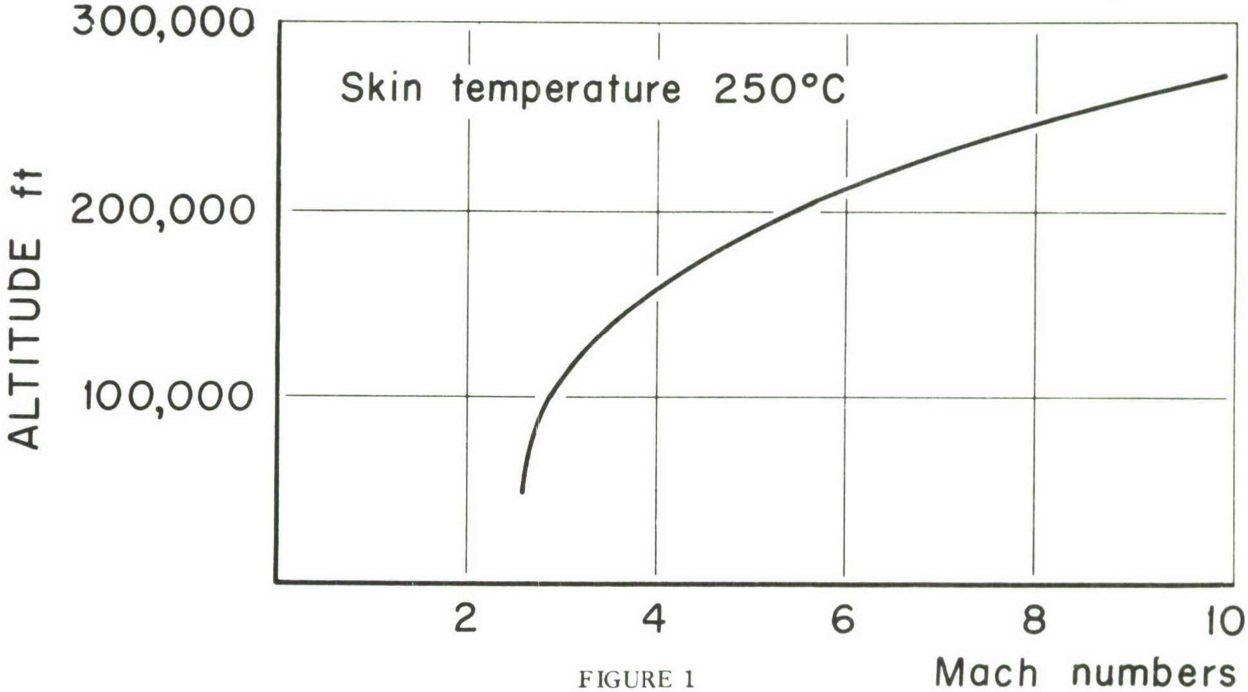

FIGURE 1

Permissible speed in Mach numbers as a function of flying altitude for a given skin temperature of 250° C. (482° F.). Line indicates 250° C. Skin temperatures are greater than 250° C. to the right and smaller to the left of the line.

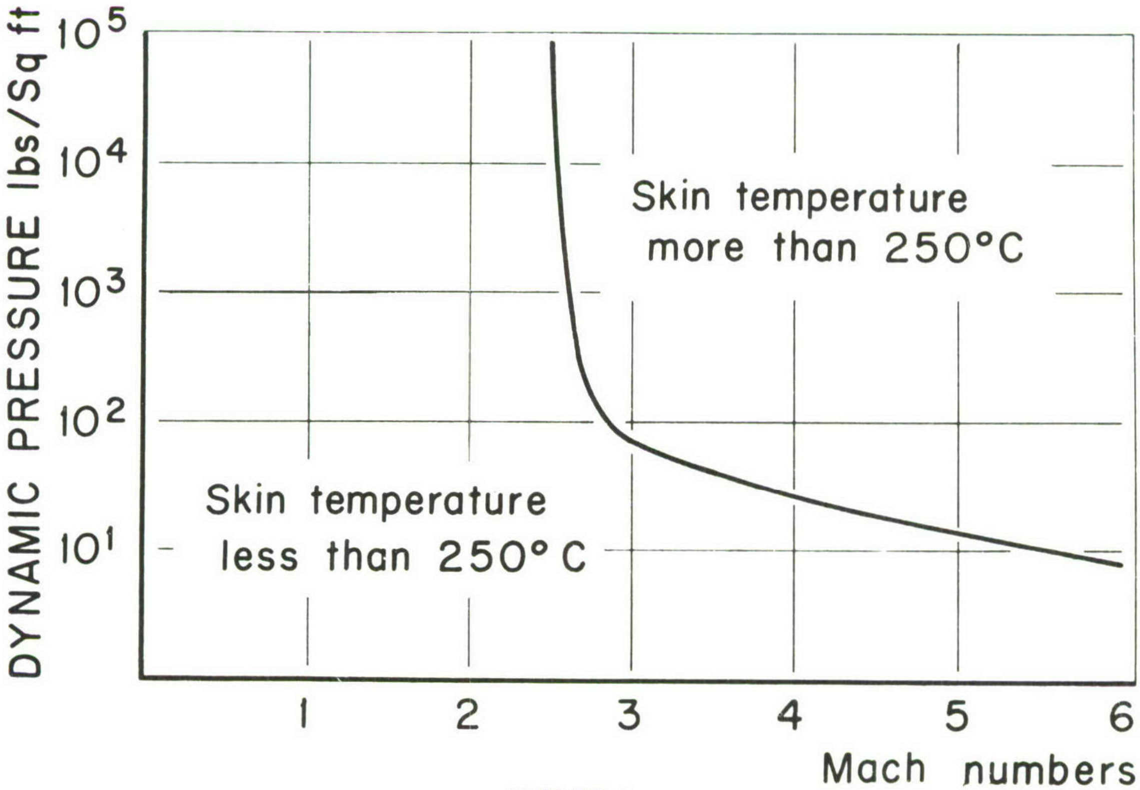

FIGURE 2

Dynamic pressure as a function of flying speed in Mach number under conditions of 250° C. skin temperature.

pressure, for future aircraft. Since the forces of windblast are a direct function of the dynamic pressure, these also can be expected to decrease.

The increasing dynamic pressure in the past has made it necessary to use an ejection seat for safe escape from an airplane. It is tacitly assured that the problems of bailing out will be enhanced in future airplanes. The anticipated falling trend in dynamic pressure, however, grants a more favorable outlook. The relief obtained is a matter of small dynamic pressures.

It is not the objective of this report to arrive at factual figures. Development of special materials and insulation might permit higher speeds at lower altitudes. However, the fact remains that for thermal reasons fast airplanes will be forced to fly at extremely high altitudes which reduce the dangers of windblast. At least this is true for rocket craft. Airplanes with air-breathing engines have a limited flying altitude where they still encounter appreciable dynamic pressures. The forces of windblast, therefore, will no doubt continue to rise but should finally level off.

The next phase in emergency escape is the free fall. The pilot will be in this state after escaping from his aircraft and before opening his parachute. In conventional bailouts this state need be of only short duration and is not considered dangerous. In order to avoid the severe opening shock of parachutes at high altitudes, it is advisable to make a delayed opening of the parachute. Thus, the free fall after bailout from high altitudes will consume much more time than after a conventional bailout. Also, the time history of the speed during the fall will be considerably different.

It is well known that a falling body is accelerated in its downward motion by the attraction of the earth. Because of the increasing speed, the air resistance grows until it equals the weight of the body. In this state of equilibrium the body is no longer accelerated but continues to fall with a constant velocity. This velocity is called the *terminal velocity*, which, for a given body, depends on altitude. At high altitudes the terminal velocity is greater than at sea level. At altitudes around 100,000 feet the terminal velocity approaches the speed of sound. The air resistance of a body flying at Mach number 1 is considerably higher than at subsonic speed. This increase will affect the terminal velocity as it approaches sonic speed.

To date, no information has been obtained on the air resistance of the human body at supersonic speeds. Measurements made on blunt objects give evidence of about a threefold increase in drag. The same increase was assumed for the calculations for figure 3 which shows the transition in the sonic range.

The *terminal velocity* or final rate of descent is a term which is used frequently in the discussions of free fall. Actually this speed is never quite matched by a falling body. A closeup study of the interplay of the force of gravity and the air resistance reveals the fact that the body overshoots the terminal velocity to a certain extent. Figure 4 shows the conditions for a free fall from conventional altitude. The velocity reaches a distinctive maximum and tapers off again at lower altitudes, but is always a few percent greater than the terminal velocity. Unfortunately a general solution of the differential equation of the time history of the velocity is impossible. An approximate solution has been obtained by a stepwise calculation, carried out by the Department of Biometrics at the USAF School of Aviation Medicine.

It was shown that a free-falling body attains and overshoots the terminal velocity after a relatively short time. Thereafter the deviation from the terminal velocity at every altitude is very small and the body arrives at sea level with a speed that is only a fraction greater than the terminal velocity of 100 m.p.h. With an initial altitude of 60,000 feet the same result is reached—that is, a final velocity of 100 m.p.h. at sea level. An increase of initial altitude to 100,000 feet does not change it. Figure 5 shows examples. In all cases, it can be seen that the final velocity is the same. This is true even if the fall begins at extreme altitudes. A human body arriving at the top of the atmosphere with escape velocity* would be a most extreme case; but even under these circumstances the final velocity is over 100 m.p.h. after the body has fallen through the entire atmosphere to sea level. With the atmosphere acting as a powerful brake to cut down the high initial speed, it would seem conceivable that a parachute could be used to brake the remainder of the speed and permit a safe landing.

It has been shown in the foregoing paragraph that the speed during the free fall varies greatly. In falling from an altitude over 100,000 feet a body attains a speed greater than that of sound but arrives at sea level with a final speed around 100 m.p.h. Now, where does the body lose all its speed? For a closer investigation of this problem,

*Escape velocity is 7 miles per second and is that speed attained by a body falling from outer space to earth.

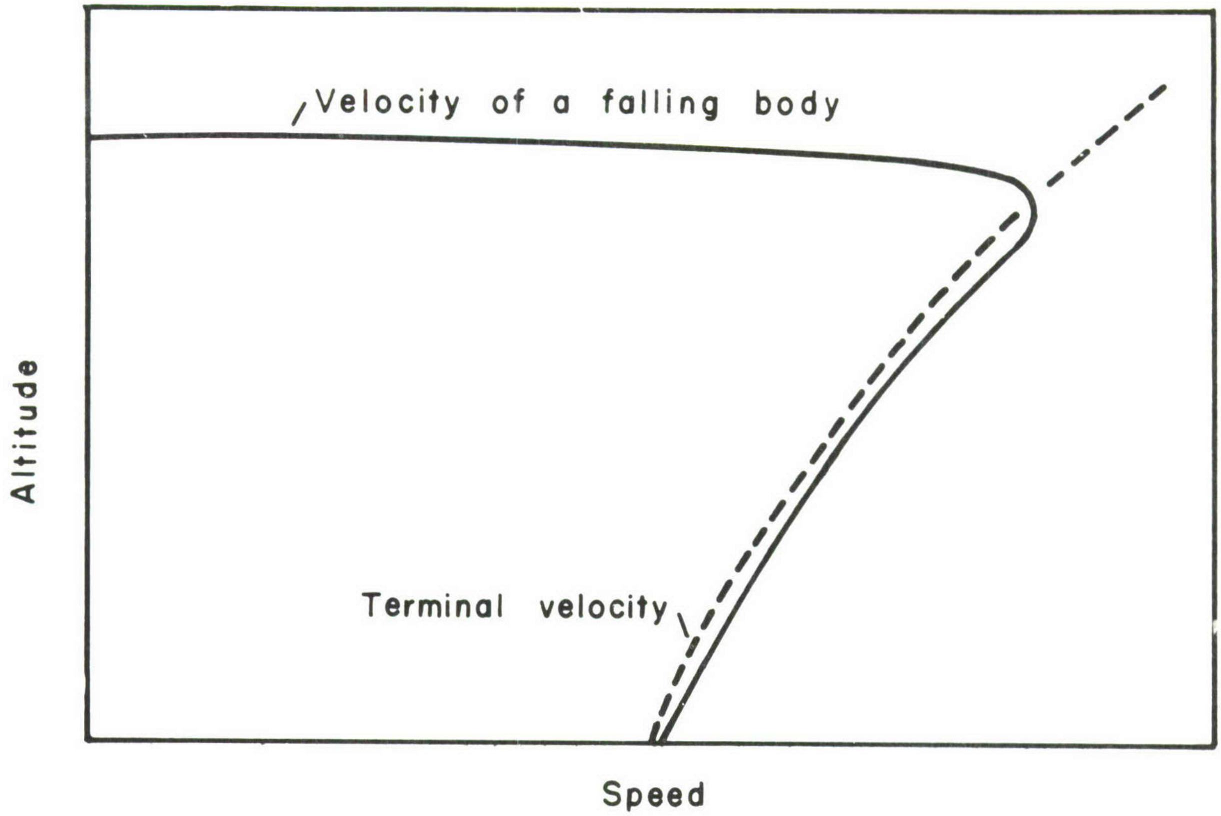

FIGURE 3

Terminal velocity of a human body in free fall as a function of altitude.

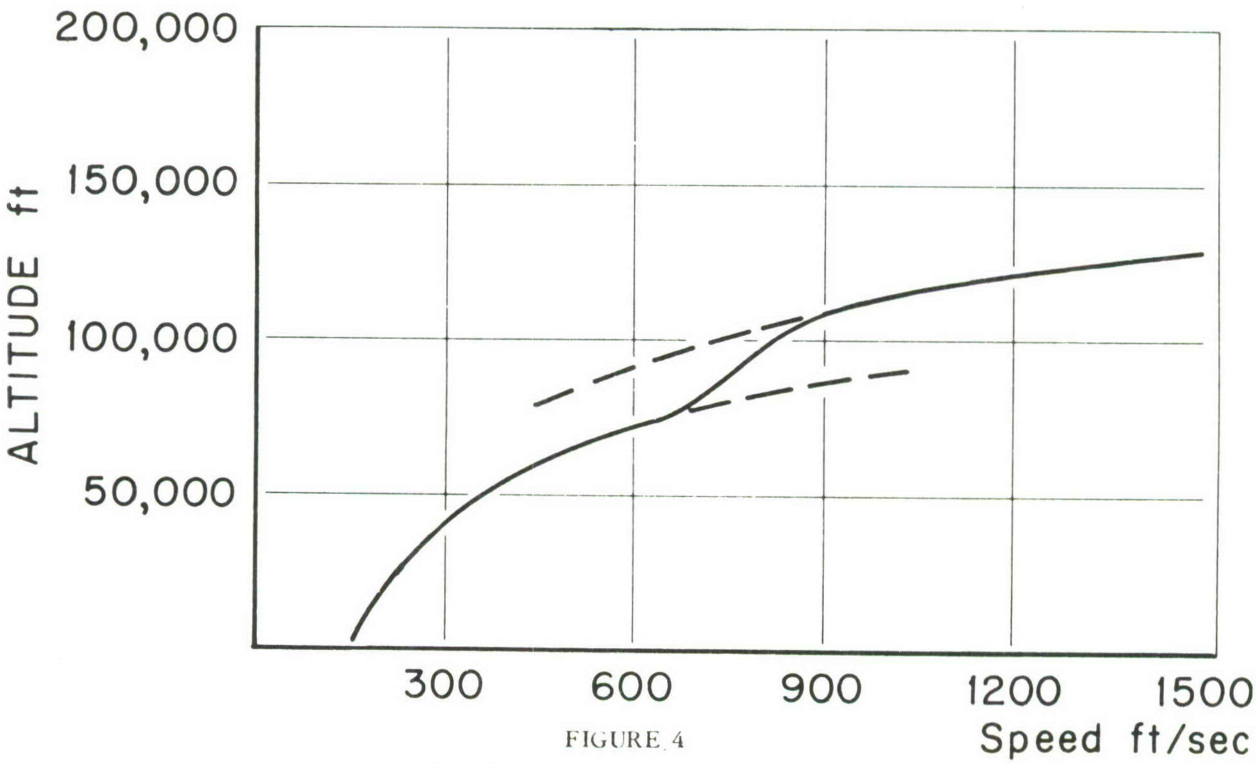

FIGURE 4

Velocity pattern of a falling body.

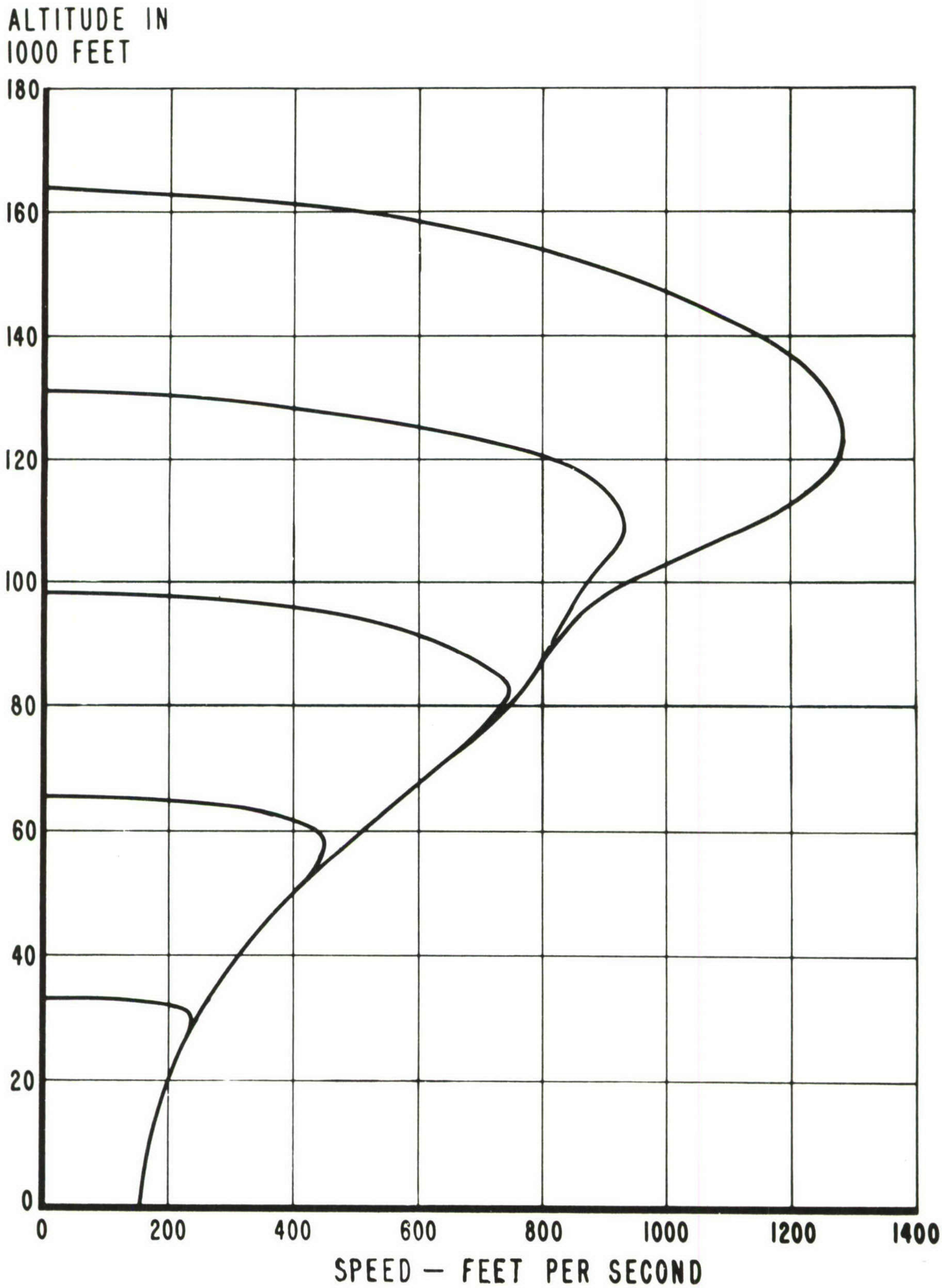

FIGURE 5

Velocity of a body falling from five different initial altitudes.

take for example a fall from 300,000 feet and direct attention to the deceleration encountered during the fall. In the beginning of the fall, the body is weightless because there is no force supporting it. Speed is picked up rapidly attaining a maximum in order of Mach number 3, and is then decelerated to terminal velocity. The cause for this change in velocity is the air drag which rises as the body gains speed and loses altitude. The air resistance soon exceeds the weight of the body, and the acceleration turns into deceleration which, in this case, reaches a value as high as 3 to 4 g's. Deceleration then falls back close to 1 g. Figure 6 depicts this example.

Decelerations of 3 to 4 g's lasting for 1 to 2 minutes are tolerable. However, the level of deceleration increases with increasing initial altitude. Considering again the case of a man arriving at the top of the atmosphere with escape velocity, the maximum deceleration is found to be in the order of 300 g. Nobody could withstand this. It can no longer be considered just a braking effect of the atmosphere but it must be considered a crash. Such a collision with the atmosphere would give rise to all the detrimental consequences. Thus, it is an astonishing fact that a man, falling from outer space back to earth, would have a speed at sea level safe for parachute landing, but he would not survive to this point because he is first subjected to the fatal impact of encountering the atmosphere.

The entire problem can be treated mathematically under the assumptions of an isothermal atmosphere and of a constant drag area. It can be shown that an important factor is the *weight over drag area,* that in comparison to wing loading might be called *drag area loading,* a term that is measured in units of a pressure.

The analysis shows that the ratio of air pressure to drag area loading is a determining factor for maximum deceleration. This ratio decreases for a given drag area loading if the altitude is increased, or for a given altitude, if the drag area loading is increased. The maximum deceleration is a function of the ratio, air pressure at bailout altitude to drag area loading. Figure 7 shows this function in

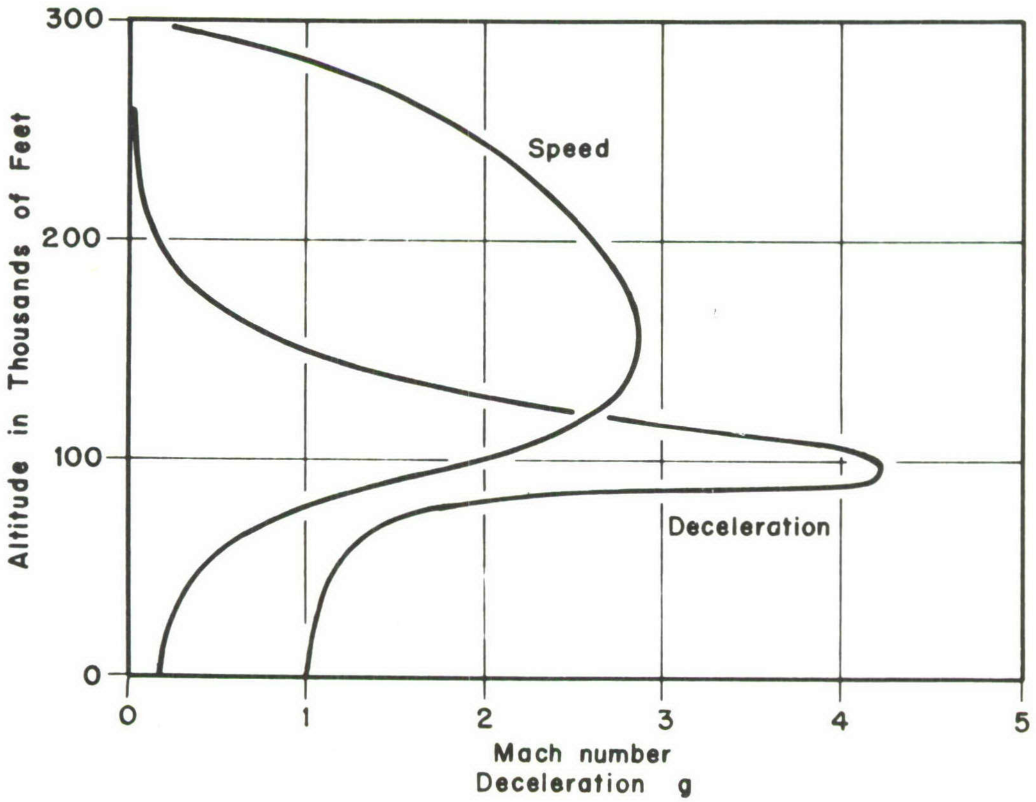

FIGURE 6

Speed and deceleration of a falling body as a function of altitude. Initial speed is zero.

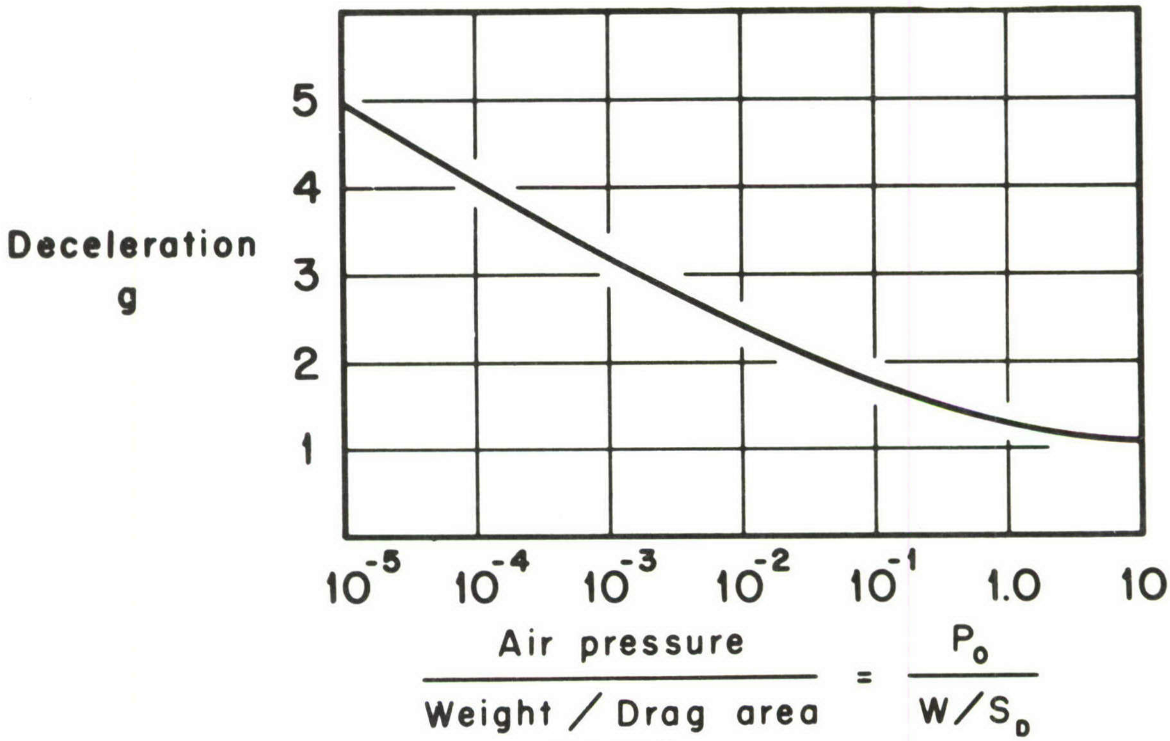

FIGURE 7

Maximum of deceleration as a function of the ratio air pressure P_o at initial altitude to drag area loading w/S_D.

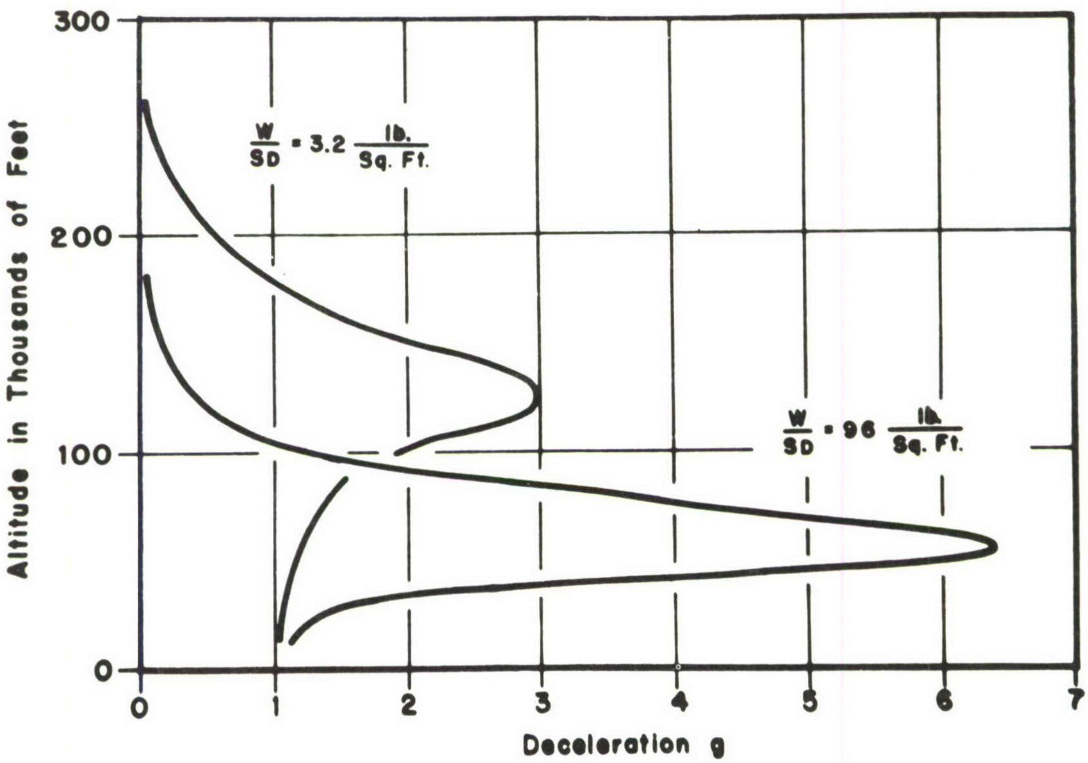

FIGURE 8

Deceleration of falling bodies with different drag area loadings.

logarithmic units. It can be seen that the smaller the ratio the greater is the maximum deceleration. This leads to the conclusion that a body with a great drag area loading (i.e., small air resistance) experiences higher deceleration. It is caused by the fact that such a body picks up more speed and plunges deeper into the denser layers of the atmosphere before being braked. Figure 8 shows this effect. It is prepared for two different values of drag area loading—that is, for 3.2 lb./sq. ft. and another one for 96.0 lb./sq. ft. The initial altitude is 300,000 feet. It can be clearly seen how the body with the higher drag area loading gains more velocity and goes deeper into the atmosphere before losing its momentum and therefore experiences higher g-forces. The analysis shows that the maximum deceleration occurs at an altitude where the air pressure is greater than the drag area loading.

There is an important conclusion which can be drawn from the above-stated facts. It has recently been considered that the escape from fast-flying aircraft should be performed by means of a capsule. It must be assumed that a capsule has a greater drag area loading than a human body. Therefore, higher g-forces must be anticipated in the phase of deceleration during the free fall. For this reason the capsule should not be made too sleek, but should have airbrakes or a small parachute for the purpose of increasing the air resistance from the beginning of the fall.

The example of a falling body starting out with zero speed is well suited for showing the interplay of the different forces. However, this is purely an academic case, because it is practically impossible to drop a body from a point at rest in these extreme altitudes. Normally, the bailout will be made from an airplane flying with considerable speed. Assuming Mach number 10 as initial velocity, the deceleration in the horizontal direction at bailout is around 0.1 g. The force of gravity is partially offset by the centrifugal force of the circulatory motion around the earth reducing the downward acceleration to 80 percent of the acceleration of gravity.

Figure 9 shows the velocity and deceleration as a function of altitude. The deceleration is small at the beginning, but increases significantly at lower altitudes. The maximum deceleration is in the order of 7 g. The influence of the air resistance is the same as above; that is, a body with a small air resistance is bound to plunge deeper into the atmosphere and to experience higher g-forces in deceleration. Thus, the same reasoning as above should be applied to the design of capsules.

Still another problem is posed by the g forces. At the beginning of the fall, the man is practically without weight. The man will be below 1 g for a period of 1 minute. For the next 2½ minutes gravity will be well over 1 g with a peak of 7 g's. It is very probable that a free-falling body will begin to tumble. Since the area exposed to the windstream changes if the body tumbles, the g forces will vary according to the tumbling motion. It can be anticipated that fluctuations of 1 or 2 g will occur. Thus, the man will be subjected, first, to subgravity and then to a pattern of fluctuating g forces together with the annoying forces of the rotation—a situation very likely to cause airsickness.

The tumbling motion apparently is a very uncomfortable experience (1). The idea of giving the man a small parachute, or some other stabilizing device in order to prevent spinning, seems advisable. However, another point is worth noting. It is well known that prolonged application of great g-forces to a human body causes the blood to pool, either in the feet or the head, depending on the direction of the g-forces. That effect actually determines the human tolerance to prolonged g-forces. The pooling of blood of course requires some time. If the body spins around its center of gravity the direction of the g-forces changes according to the rotation of the body. It is very likely that the blood will remain where it is since it will not have enough time to flow from the one extremity to the other. Such an affect of course is equivalent to an increased g-tolerance, but just how much of an increase is not yet known. Spinning, therefore, should not be prevented (2).

Spinning of course has its drawback. Benefit is obtainable only if the rate of spinning is not too great (3). If the rotation is too fast, then pooling of the blood occurs on account of the centrifugal g-forces produced by the rotation itself. In experimental jumps made from 30,000 to 40,000 feet, the rate of tumbling was quite tolerable. However, it is likely that at extremely high altitudes the speed of rotation will increase, because the forces exciting the rotation increase in the same order as do linear g-forces, whereas, the dampening forces determining the final rate will be much less on account of the small air density. On the other hand, it is not known what influence supersonic speed will have on all these factors. After all, the entire problem is still completely open.

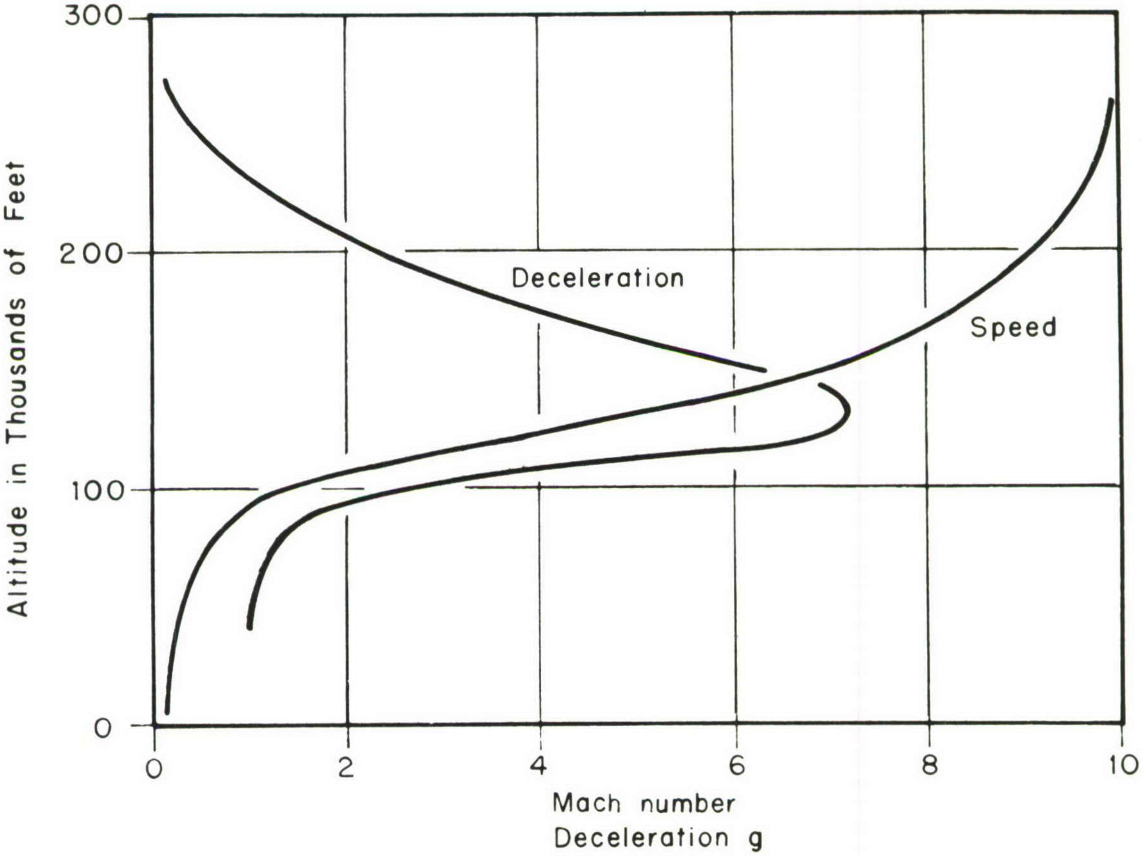

FIGURE 9

Speed and deceleration of a falling body as function of altitude. Initial speed is Mach 10.

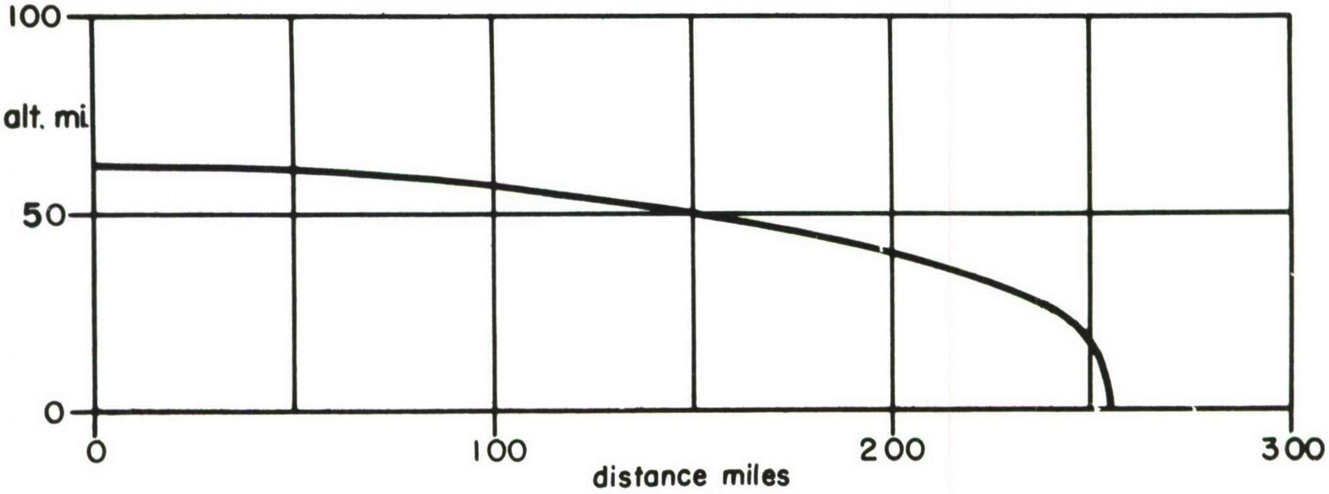

FIGURE 10

Trajectory of a falling body. Initial speed, Mach 10.

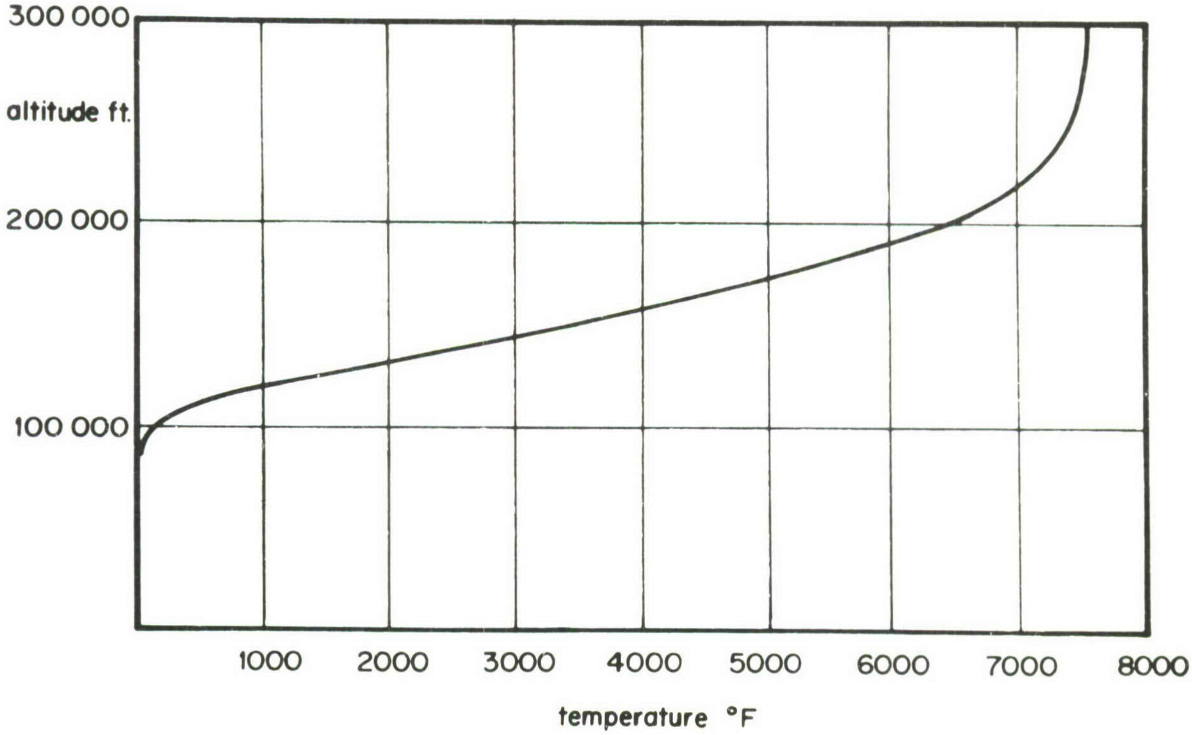

FIGURE 11

Friction temperature of the air surrounding a fallen body.

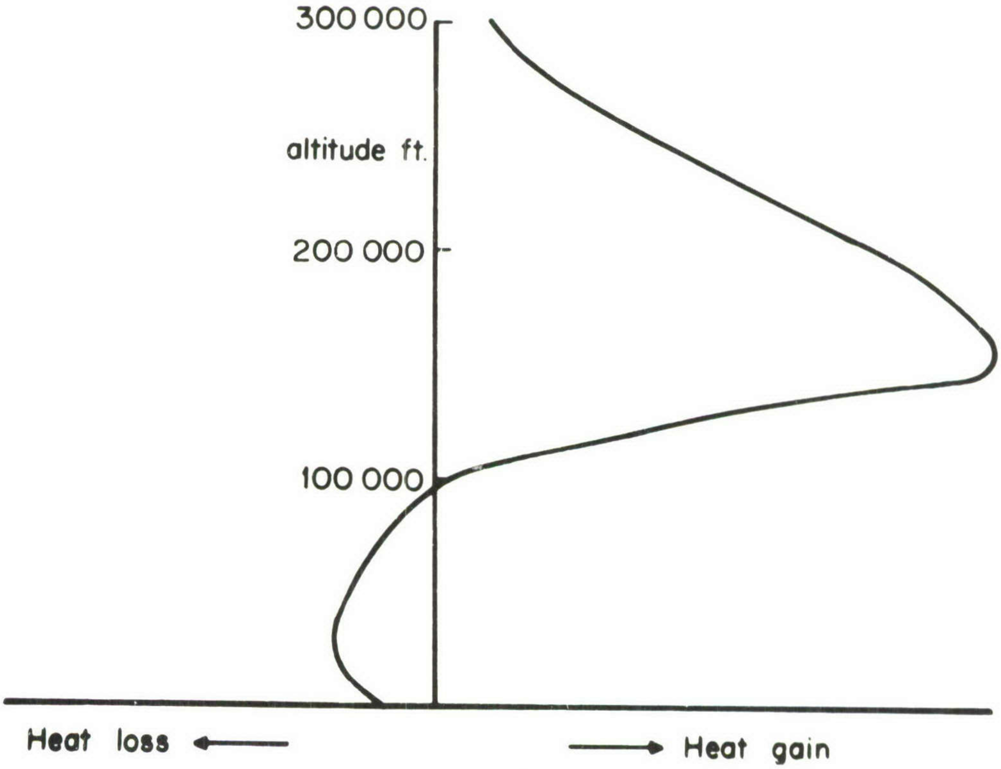

FIGURE 12

Heat gain and loss of a falling body as function of altitude.

The high horizontal speed at bailout has a surprising side effect. Before the downward speed increased to a considerable value, the distance covered in horizontal direction assumes appreciable proportions. Figure 10 shows the shape of the trajectory. Before reaching the ground after bailing out at 300,000 feet at Mach number 10, the man travels about 250 miles in the horizontal direction. For instance, a man bailing out over Washington, D.C., would land in New York, 250 miles away. This presents a specific danger involved in high-altitude bailout, because the long distances traveled pose the problem of locating the man after he has landed. The search must cover an area of 500 miles in diameter.

In discussing the physical facts of high-altitude bailout, one should not forget the aerodynamic heating of the falling man. It is known that at high speed the air surrounding a body is heated to a certain temperature above the level of the ambient temperature. A rule of thumb says that this rise is 75 times $(\text{Mach})^2$ in degrees Fahrenheit. A speed of Mach number 10 therefore yields a temperature of 7,500° F.

Figure 11 shows these temperatures occurring during a fall and depicts the fact that the high temperatures disappear as soon as the speed decreases at lower altitudes.

It is not the temperature, however, which is dangerous but the heat transferred to the body. Thus, heat transfer is small at high altitudes on account of the low air density. Figure 12 shows an estimation of the heat flow. It is interesting to note that the recent problems of keeping a man warm enough after bailout at 30,000 feet are now reversed. The heat gain is greater than the heat loss at lower altitudes, so that it is a problem to keep a man cool enough.

The following consideration gives an estimation of the heat problem involved: The body, falling from very high altitudes, attains a certain speed when it reaches an altitude of 30,000 feet. This speed is about the same as if the body had fallen from 40,000 feet. The heat loss—represented in the lower part of figure 12—is known in such cases, since numerous jumps have been made from this altitude. A comparison of this heat loss to the heat gain in higher altitudes—as shown in the upper part of figure 12—illustrates the importance of these problems. Thus, any protective equipment must serve the double purpose of keeping a man cool at high altitudes and warm at low altitudes where low ambient air temperatures prevail in conjunction with low speeds.

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COMPARATIVE ECOLOGICAL STUDY OF THE CHEMISTRY OF THE PLANETARY ATMOSPHERES

HUBERTUS STRUGHOLD, Ph.D, M.D.

Department of Space Medicine

SPECIAL REPORT

Air University

USAF SCHOOL OF AVIATION MEDICINE
RANDOLPH FIELD, TEXAS
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COMPARATIVE ECOLOGICAL STUDY OF THE CHEMISTRY OF THE PLANETARY ATMOSPHERES

The comparative study of planetary atmospheres has become a major topic in recent astronomical literature (8, 9, 12, 20, 21, 22, 28, 30). It might be of considerable interest to view the planetary atmospheres also from a biological point of view. This has been done by the writer in former publications with regard to temperature (23, 24). An attempt will be made in the following discussion to examine the *chemistry* of the planetary atmospheres from a biological point of view. This will enable us to differentiate between certain characteristic *types of atmospheres.*

In comparing the planetary atmospheres as to their biological—or more precisely, ecological—qualities, it is logical to start with the earth's atmosphere as the one of reference (6, 33). In addition, it is important to include in such a study the various stages in the historical development of this atmosphere.

The *present-day atmosphere of the earth* has a mass of 5.2×10^{21} gm. or 5.2 quadrillion metric tons. Of this air mass 1.2×10^{21} gm. is oxygen (O_2); 2.0×10^{18} gm. is carbon dioxide (CO_2). The amount of water and water vapor in the total atmosphere is around 1.5×10^{19} gm. Here we ignore the inert gases, since only the aforementioned components are those which give the atmosphere its biological characteristics. It is the *free oxygen* (O_2) which is the most suitable yardstick in an ecological classification of the planetary atmospheres. With oxygen, an atmosphere possesses *actual or manifest oxidizing power.** The strong oxidizing power found in our atmosphere has been and still is the basis for the existence and development of higher plants, animals, and man. This oxidizing capability decreases with increasing altitude—a fact which has been the main topic of discussion for physical and physiological research ever since the air became a medium of transportation (1, 33). In addition to the actual oxidizing power, the atmosphere possesses a *potential* or latent oxidizing power, the explanation of which will be given later.

The *chemical composition* of our atmosphere has not always been the same. It has undergone drastic changes in the course of its development from the protoatmosphere to its present stage. These changes have been discussed in a most inspiring manner in the recently published books of Kuiper (12) and Urey (28).

The *protoatmosphere* of the earth is understood as that gaseous envelope which surrounded our planet during its developmental stage as a protoplanet, or protoearth. This stage embraced the range of time during which the accumulation of the solar dust and planetesimals into a planetary body was completed—or nearly completed—and finally the surface was formed into a semisolid to solid crust. It was at the time that the temperature approached its present-day level. This particular range of time can be estimated at about 2 to 2½ billion years ago—near the turn from astronomical or pregeological time to geological time.

The protoatmosphere so defined showed a chemical composition very different from that of the present-day atmosphere (12, 28). The principal components in the order of their abundance can be seen in table I.

Since this atmosphere contained mainly hydrogen and hydrogen compounds such as water, methane, and ammonia—but no oxygen or carbon dioxide—this type of atmosphere is a *reducing* and a *reduced atmosphere.* It has no actual oxidizing power but contains potential or latent oxidizing power. This potential or latent oxidizing power is hidden in the water molecule.

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*Monatomic oxygen (O) and triatomic oxygen (O_3, ozone) are ignored here, since diatomic oxygen (O_2) only is important in the process of biological oxidation.

The expressions "oxidizing and oxidized" and "reducing and reduced" conditions of an atmosphere are used by H. Urey (28) in his geochemical discussion of the historical development of the atmospheres. Confined to the biological temperature range, they may also be convenient terms for biological and aeromedical discussions like this. Oxidation and reduction are used here in their original conception: *oxidation*—union with oxygen or removal of hydrogen; *reduction*—union with hydrogen or removal of oxygen.

According to Tammann (26) and Wild (34) the water molecules have been thermally decomposed into hydrogen and oxygen at the border zone of the protoatmosphere. According to Harteck and Jensen (7), Poole (18), and Suess (25), they have been split by photodissociation.* The hydrogen escaped into space, and the oxygen remained. With the appearance of this ***initial oxygen*** the gaseous envelope of the earth attained actual oxidizing power. It became an ***oxidizing atmosphere.*** This started a new step in development. Ammonia (NH_3) was oxidized to free nitrogen (N_2) and water (H_2O), and methane (CH_4) to carbon dioxide (CO_2) and water. In addition, large amounts of carbon dioxide (CO_2) were injected into the air by volcanic exhalations.

During this process of evolution, the atmosphere represented a ***mixed medium*** with both reduced and oxidized compounds. It was a ***suboxidized atmosphere*** with a high potential and, to some extent with an actual, oxidizing power. However, the development continued in the direction of a ***highly oxidized atmosphere.*** This process was accelerated by the appearance of chlorophyll (5). If this molecule is present, the combination of water plus carbon dioxide offers a new possibility for producing oxygen if sunlight is adequate. The process in question is ***photosynthesis.*** The oxygen produced in this process oxidized the rest of the reduced compounds, and was accumulated in rather large amounts—such as those observed today in our atmosphere. Thus the present-day atmosphere is a gaseous mixture still with a high potential oxidizing power as well as a strong actual one. With chlorophyll present, the high potential oxidizing power is based on the inexhaustible amounts of water in the oceans (1.4×10^{24} gm.) and on the large supply of carbon dioxide.

Concluding this part of the discussion, it might be of interest to note that in the transformation of the protoatmosphere to the present-day atmosphere, with regard to the molecular weight, the chemical components have shifted from lighter to heavier ones. For more detail see Kuiper (12).

*Chemical processes of this and other kinds are still going on in some areas of the present-day upper atmosphere for which Kaplan (11) recently coined the term "chemosphere."

TABLE I

Main components of the terrestrial protoatmosphere and atmosphere in order of abundance

Protoatmosphere	H_2	He	Ne	H_2O	NH_3	CH_4	A
Atmosphere	N_2	O_2	H_2O	A	CO_2		

Summarizing, we find in the historical development of the terrestrial atmosphere three types of atmospheres:

I. A ***reducing and reduced atmosphere*** with a potential but no actual oxidizing power—a ***nonoxidizing atmosphere.*** In this anoxic atmosphere, which was found in the early phase of the protoatmosphere, organisms are hardly conceivable. If, however, organic compounds like amino acids were produced by solar radiation (3, 15, 17, 28) with some CO_2 available, anoxibionts could have existed in this primitive atmosphere.

II. ***A transitional stage*** in the form of a partly reduced and partly oxidized atmosphere, with potential and increasing actual oxidizing power. In this stage of the protoatmosphere, chemoautotrophs (iron, sulfur, and ammonia bacteria) and photoautotrophs (chlorophyll-bearing organisms of lower order) could have existed.

III. A ***highly oxidized*** atmosphere with strong actual oxidizing and high potential oxidizing power. This type of atmosphere, which we observe today, provided the basis for the development of higher plants, animals, and man.

This survey of the chemical characteristics of the earth's atmosphere during its development from the protoatmosphere to the present-day atmosphere (or neoatmosphere) facilitates the understanding of those of the ***other planets*** (10, 12, 14, 22, 28, 34).

A decisive factor in the chemistry of a planetary atmosphere is the ***distance from the sun*** and the resulting intensity of radiation. As mentioned earlier, radiation causes photochemical reactions, especially at the border zone of the atmosphere. Another factor in the evolution of an atmosphere is the ***escape*** of the molecules into space. This phenomenon is dependent upon the temperature and mass of the planet.

In the following we shall consider the planets—not with increasing distance, as is usually done—but rather with decreasing distance from the sun, since this sequence conforms better with the foregoing discussion concerning the historical development of the terrestrial atmosphere.

Table II shows the main chemical components of the planetary atmospheres in the order of their abundance. Since the distance from the sun and the resulting solar constants and temperatures have a great influence on the chemical composition, their respective values are added.

Approaching the solar system from the outside, we first encounter ***Pluto***, the outermost planet. The solar constant of Pluto is only 1,600th that of the earth. The maximum temperature on Pluto is around 60° K. (about −210° C.). The chemical composition is not known. It is assumed that it consists of hydrogen, helium, and methane.

Neptune, Uranus, Saturn, and ***Jupiter*** can be considered here as a group. The atmospheres of these larger planets consist mainly of hydrogen, helium, methane, ammonia, and probably water. The similarity of this composition to that of the protoatmosphere of the earth is striking. Apparently, escape of these light components has been prevented because of the strong gravitational forces of these planets. They seem to be preserved in a frozen state because of their greater distance from the sun.

Table II shows no ammonia in the more distant planets Uranus and Neptune. This has been explained with the different freezing points of ammonia (−77° C.) and of methane (−184° C.) (10, 12, 26). At the extremely low temperatures on Neptune and Uranus, only traces of ammonia exist as vapor. Their atmospheres are relatively strong in gaseous methane. On Saturn, with a temperature of about −165° C., and on Jupiter with −130° to −140° C., less ammonia would be frozen and more would exist in the form of vapor.

The atmospheres of the larger planets (and Pluto) containing hydrogen and hydrogen compounds are reduced atmospheres. They have no actual oxidizing power since there is no oxygen. They may have latent oxidizing power, if water (frozen) is found in some layers. Because of the great distance from the sun, however, it is questionable if this potential power will ever be released. For this reason, none of these planets offer a suitable ecological environment for any known kind of organism. The atmospheres are comparable to the terrestrial protoatmosphere in its early phase. In addition to this chemical point of view, the temperature of this entire group of planets is so low that active life is prohibited.

The main constituents in the Martian atmosphere are probably nitrogen and argon (9, 12, 23, 28, 29). The amount of CO_2 is higher than on earth (12). Water is present in very small amounts, mainly in the form of ice and vapor (12). This atmosphere is qualitatively similar to that of the earth, except that it contains no oxygen, or only traces of it. Quantitatively, it is comparable to the upper terrestrial atmosphere (above the 11-mile level). During its evolution Mars lost most of its atmosphere because of its low gravitational force. Not only hydrogen but also oxygen might have escaped from proto-Mars. The ***Martian atmosphere is an oxidized atmosphere*** with low potential oxidizing power. This may be sufficient to permit the existence of vegetation of lower order (12, 14). The actual oxidizing

TABLE II

Components of the planetary atmospheres

Planet	Solar constant (earth = 1)	Maximum temperature (°K.)*	Most important probable atmospheric components in order of abundance**				
Pluto	1/1600	60	H_2	He	(CH_4)		
Neptune	1/900	56	H_2	He	CH_4	(NH_3)	(H_2O)
Uranus	1/400	69	H_2	He	CH_4	(NH_3)	(H_2O)
Saturn	1/100	107	H_2	He	CH_4	NH_3	(H_2O)
Jupiter	1/25	145	H_2	He	CH_4	NH_3	(H_2O)
Mars	3/7	307	N_2?	A?	CO_2	H_2O	
Earth	1	349	N_2	O_2	H_2O	A	CO_2
Venus	2	324	N_2?	CO_2			
Mercury	6	625					

*According to Kuiper (12).
**According to Hess (9), Kuiper (12), and Urey (28).
( )Probably present in a frozen state only.

power may be very weak or nonexistent, depending on the presence or absence of free oxygen.

Venus probably contains nitrogen and carbon dioxide—the latter in large amounts—but no water or oxygen (9, 12, 28). The Venusian atmosphere is a ***completely oxidized atmosphere.*** If it does not contain water and oxygen, it has, therefore, no potential nor actual oxidizing power.* This being true, it could not support any kind of life. However, this point is still a matter of astronomical dispute.

Table III gives a summary on the types of planetary atmospheres as they must be considered from a biological point of view. The first type (protoatmosphere and outer planets) is essentially a hydrogen atmosphere. The second type (transitional atmosphere) is a hydrogen-oxygen atmosphere. The third type (present-day atmosphere of the earth) must be characterized as an oxygen atmosphere. The fourth type (Mars) is a carbon dioxide-water vapor atmosphere, and the fifth type is a carbon dioxide atmosphere. The classification may be somewhat artificial. However, by and large, it complies essentially with astronomical considerations, as well as with biological ones. It clarifies the ecological qualities of the planetary atmospheres insofar as their chemistry is concerned. In particular, it demonstrates clearly the position of the terrestrial atmosphere.

*This is true if we ignore CO_2 as a possible source of oxygen, as Arrhenius (2) suggested.

TABLE III

Ecological types of atmospheres of the planetary system

Type	Main components	Chemical characteristics	Oxidizing capability	Oxygen condition*	Planet
I Hydrogen atmosphere	Hydrogen Hydrogen-compounds	Reduced atmosphere	Potential oxidizing power; no actual oxidizing power	Anoxic	Outer planets; protoatmosphere of earth, early phase
II Hydrogen oxygen atmosphere	Hydrogen Hydrogen-compounds Oxides Oxygen	Transitional atmosphere (partly reduced and partly oxidized)	Potential and increasing actual oxidizing power	Hypoxic	Protoatmosphere of earth, later phase
III Oxygen atmosphere	Oxygen Oxides Hydrogen-compounds	Highly oxidized	High actual and high potential oxidizing power	Normoxic	Present-day atmosphere of earth
IV Carbon dioxide-water vapor atmosphere	Oxides Hydrogen-compounds	Highly oxidized	Low potential oxidizing power low or no actual oxidizing power	Hypoxic or anoxic	Mars
V Carbon dioxide atmosphere	Oxides	Highly oxidized	No potential oxidizing power; no actual oxidizing power	Anoxic	Venus

*Anoxia – no oxygen at all.
Hypoxia – low oxygen concentration.
Normoxia – normal oxygen concentration as found at or near sea level on earth.
From a biological point of view the oxygen condition on earth is taken as the normal standard condition.

In aeromedical parlance, with the exception of the atmosphere of earth, all planetary atmospheres are anoxic or hypoxic atmospheres. Those of the larger planets are still primarily anoxic; those of Mars and Venus may be already secondarily hypoxic or anoxic. Therefore, despite the probability that according to the theory of von Weizsaeker (32), Ter Haar (27), Kuiper (12), and Urey (28), all planets originated about the same time and therefore have the same age—chronologically, the outer planets are younger than the inner planets insofar as their atmospheric metabolic life cycle is concerned.

In conclusion, as previously mentioned with regard to the development of the terrestrial atmosphere, the consideration of the molecular weight of the chemical components of the present-day planetary atmospheres is of interest. Table IV shows these components in the order of their molecular weight. It indicates that they shift from lighter molecular weight to heavier compounds with decreasing distance from the sun. This has, as previously mentioned, some relation to escape into space, which is dependent upon the temperature and gravitational force of the planet.

The space shown in table IV between Jupiter and Mars represents the belt of asteroids. If these asteroids have originated from a former planet—the so-called "Meteorite" planet—and if this planet were about the same size as the earth, from this table we could deduce the probable chemical composition of the atmosphere and the possibility of life on this perished Atlantis in the solar system. If this planet existed today, it might perhaps show the transitional type of atmosphere (type II). But it is also possible that disturbances by the gravitational field of Jupiter, or physical properties of the accumulating material (coagulating effect of frozen water (28)), prevented the planetesimals from forming a planet.

At this point a brief remark about the *comets* seems appropriate. According to a new comet model suggested by Whipple (31) the cometary nucleus is visualized as a conglomerate of lumps of meteoritic material held together by various ices such as water, ammonia, methane, and others, all initially at low temperatures (250° K.). The place of origin of the comets is probably beyond the planetary system.

Basically, the volatile components of Whipple's comet model are nearly the same as the chemical components of the protoatmosphere of earth and the present-day atmospheres of the outer planets. If a comet approaches within three astronomical units* of the sun, the frozen ammonia, methane, and water evaporate, and under the effect of solar radiation similar photochemical reactions take place as they did in the primitive atmospheres of the inner planets. By photodissociation and photo-ionization from the aforementioned (not observed) hydrogen compounds as parent molecules, substances like OH, NH, CN, CO, and N_2, etc., which have been observed spectroscopically in the tail or the head of the comet, are produced.

In this way the comets periodically undergo, in the matter of months, about the same process which took place in the atmospheres of the primitive inner planets over a period of hundreds of millions of years. At the same time these ice mountains in space lose during each revolution about 1/2000th of their mass. After several hundreds of such photochemical events the comets disintegrate and disappear forever—like the Biela Comet in 1846.

Showers of *meteorites* are assumed to be the remnants of disintegrated comets (13, 16). Among the gases found in heated meteorite powder (10) are vapors of hydrogen, carbon monoxide, carbon dioxide, nitrogen, and methane—again a combination of compounds which are similar to those found in types I and II of the above-described ecological classification of the planetary atmospheres of the solar system.

Before ending this study the author wishes to state that its preparation was possible because of his reliance upon the extraordinary progress made in astrophysics and geochemistry as found in the attached list of references.

*One astronomical unit is equal to the distance between the sun and earth (93,000,000 miles).

TABLE IV

The main components of planetary atmospheres in the order of their molecular weight

Planet	H_2 2	He 4	CH_4 16	NH_3 17	H_2O 18	N_2 28	O_2 32	A 40	CO_2 44
Pluto	•	•	•						
Neptune	•	•	•	(•)	(•)				
Uranus	•	•	•	(•)	(•)				
Saturn	•	•	•	•	(•)				
Jupiter	•	•	•	•	(•)				
Belt of asteroids									
Mars					•	•		•	•
Earth					•	•	•	•	•
Venus						•			•
Mercury									

(•) Probably present in a frozen state only.

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MEDICAL PROBLEMS OF SPACE FLIGHT

Brigadier General Edward J. Kendricks, USAF (MC)
Hubertus Strughold, M.D., Ph. D.
Douglas Aircraft Company, Inc.
Heinz Haber, Ph. D.
Siegfried J. Gerathewohl, Ph. D.

A SPECIAL REPORT

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USAF SCHOOL OF AVIATION MEDICINE
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MEN ARE NOW FLYING IN SPACE

BRIGADIER GENERAL EDWARD J. KENDRICKS, USAF (MC)

COMMANDANT, USAF SCHOOL OF AVIATION MEDICINE

On 7 August 1951, above Muroc Dry Lake in California, a civilian test pilot, in the rocket-powered Douglas D-558-2 ("Skyrocket"), was detached from the bomb bay of a B-29 at about 30,000 feet. He started climbing, and reached 79,494 feet before he nosed over and returned to Edwards Air Force Base.

Again, during the summer of 1954, in the rocket-powered Bell X-1A, with an Air Force pilot at the controls, the same procedure was followed. This time a new altitude record—not yet officially reported—was set. Unofficial accounts have stated publicly that the X-1A attained a height of at least 88,500 feet, or 16.8 miles above the earth.

If these figures are considered simply as a measure of man's ingenuity in building and operating machines that attain ever greater heights, they are remarkable enough. But they imply more than that. For, at 88,000 feet, a flyer is more than four miles above the point which is considered by aviation physiologists the effective limit of the earth's atmosphere.

These pilots were virtually flying in space. The conditions of air pressure and oxygen supply with which they had to deal, for the few minutes that they were aloft, differed physiologically only in duration from the ones they would have encountered on a trip to Mars.

Unlike the ocean, whose density remains nearly constant as its pressure increases with depth, the atmosphere rapidly decreases both in density and in pressure. Flying at an altitude of only 18,000 feet, the pilot already has one-half the total mass of the earth's air below him. At 50,000 feet, almost 90 per cent of the atmosphere is left behind. By the time 100,000 feet—or 19 miles—is reached, a scant 1 per cent remains.

This air is thinly diffused to an enormous depth into the sky. Traces are still found as far up as 500 miles, the outer limit generally accepted by astronomers. But for all practical purposes the atmosphere ends about 12 miles (63,000 feet) above the ground. There is not enough air left at that height to burn a candle—or fly a jet. Only a rocket plane can take the airman higher. Yet 12 miles is just about the distance from New York City's Battery to the Bronx. In level flight, an F-86 can cover that distance in approximately one minute.

By breathing pure oxygen, a pilot may attain an altitude of about 38,000 feet with ordinary breathing movements, and still maintain his normal functions. One way to exceed this altitude safely is to resort to the use of a tightly-sealed face mask providing oxygen to the lungs under pressure. With such pressure-breathing oxygen equipment, currently standard in military aircraft, he may fly at 43,000 feet for prolonged periods and still maintain a normal oxygen supply to his tissues. For brief periods he may perform efficiently even at 50,000 feet, using this breathing equipment.

At approximately 63,000 feet, the atmospheric pressure drops to a mere 47 millimeters of mercury—about 6 per cent of the pressure at sea level. This is the pressure under which water boils at a temperature of 98.6° Fahrenheit, the normal temperature of the human body. Theoretically, then, the blood and other fluids in a flyer's body also will begin to boil at this altitude. From this point on, full-body pressurization is needed. He must either wear a pressurized suit or sit in a pressurized cabin.

The ambient air at this altitude is so thin that it also begins to be an impractical task to use cabin-pressurization equipment to compress it. The bulk and weight of the pressurizing equipment become prohibitive

at about 75,000 feet. Moreover, from 70,000 to 80,000 feet, the flyer passes through the peak concentration of the ozone layer in the atmosphere. It is likely that this substance, in the high concentrations forced into the cabin by a compressor, would have a deleterious effect upon the flyer.

So an aircraft designed to operate in this region above 63,000 feet for any length of time must carry its own atmosphere under pressure, sealed off completely from the near-vacuum outside. Such a craft is, in effect, a space ship. So far as its pressure and breathing equipment are concerned, it could cruise anywhere in outer space.

During the years immediately after World War II, Major General Harry G. Armstrong, then Commandant of the School of Aviation Medicine, perceived that flight in space—as here defined—was an imminent reality. Feeling that there was an urgent need to explore the medical problems of flight in the upper atmosphere, he created the Department of Space Medicine at the School, and placed a distinguished aviation physiologist and physician, Dr. Hubertus Strughold, at its head.

Dr. Strughold and his co-workers have considered all the known properties of the border zone between the troposphere, where conventional flight occurs, and outer space, with their probable effects upon the human body. The Department studies questions of heat radiation, the heavy primaries of cosmic radiation, visual disturbances in the upper air, and the peculiar phenomenon of weightlessness in certain flight maneuvers. The research of this Department is wholly basic, the application remaining for other agencies to perform.

Experimental facilities for laboratory research in space medicine are meager. Last year the first piece of apparatus designed specifically for research in space medicine was delivered to the School of Aviation Medicine. It is the prototype of the sealed aircraft cabin, discussed by Dr. Strughold in this Report. As with the low-pressure chambers of an earlier era in aviation medicine, it should be possible to answer many questions about the physiology of space flight with research in this earthbound apparatus.

Since the very beginning of aviation, the aeromedical team, consisting of flight surgeons and research scientists, has gone hand-in-hand with the engineers in the mechanical advancement of flight. Until World War II, the aeromedical team had invariably mastered most of the human problems to be encountered by the crew at the current ceiling. However, the swift development of jet planes during the War, and the rapid progress of rocket power since, have somewhat altered this situation. For the first time, men are flying in relatively unexplored reaches of the air, and space medicine is our effort to maintain the health, safety, and efficiency of the men who fly there.

The human problems of space flight unquestionably are pressing. The urge that impels airmen to thrust ever higher toward the frontiers of the sky is not merely a quest for records and prestige. Although tactical advantages afforded the combat flyer by superiority in altitude may not be so great as in the past, other features of flight compel the military air services to reach higher ceilings. For example, it is desirable to achieve the greatest possible distance above the enemy's ground-detection equipment and defenses. Again, the thin air high above the troposphere enhances both speed and range.

Rocket-powered planes may be the combat military aircraft of the future. Experimental craft such as the Douglas Skyrocket and the Bell X-1A may be considered as the precursors of tomorrow's rocket fighter.

Space may be said to be the natural habitat of a rocket ship. But, unlike the rocket, man does not find in space a natural home. Every feature of that immense and lonely, rarified region is hostile to human beings, accustomed to living under the shelter of a blanket of air. Men must therefore take their own peculiar environment with them when they venture into space. Every element that supports human life, and protects it from the unfriendly medium outside, must be supplied from within the confines of the craft.

A real task of aviation medicine today, then, is to show men how to live in space. It is a task of no small magnitude when we consider the variety of virulent conditions

which the flyer must face there. Yet the fact that we have mastered the most elementary problems—those of pressure and oxygen supply—affords genuine promise that the problems of man in space also will be conquered.

LIVING ROOM IN SPACE

HUBERTUS STRUGHOLD, M.D., Ph. D.

HEAD, DEPARTMENT OF SPACE MEDICINE
USAF SCHOOL OF AVIATION MEDICINE

Thirty years ago few men even thought about the possibility of flying beyond the the troposphere, the shell of comparatively dense air that covers the earth up to about 40,000 feet. The only serious medical problem that a pilot faced on routine flights within a few miles of the ground had to do with oxygen. Above 10,000 feet the supply of this vital gas, on which all living creatures depend for their existence, thinned to a point where the average person's faculties began to be impaired for lack of it. Above 20,000 feet the amount available was so small that the flyer would first lose consciousness and then die.

To solve this problem, the oxygen mask was developed. It simply provided an additional source of oxygen which the pilot could breathe, enriching the ambient air so that the mixture in his lungs would contain roughly the same amount of it as at sea level. This equipment served quite well until, in the nineteen-thirties, flight began to move higher toward the top of the troposphere and on into the stratosphere. Then another series of problems arose.

At somewhat higher levels of the atmosphere, the total air pressure becomes so small that the body's functions are disturbed. The gas in cavities like the stomach expands. Nitrogen bubbles form in the blood vessels and tissue, causing the painful condition popularly known as "the bends." Another device was needed to deal with these problems.

It was found about twenty years ago, in the pressurized cabin. This equipment is essentially a pump, which sucks thin air into the plane from outside and compresses it, so that it has approximately the pressure—and the oxygen content—found below 8,000 feet. In such a cabin, provided it was not punctured, letting the pressurized air escape, and provided the pumps did not fail, the flyer could be as comfortable at quite high altitudes as if he were on the ground.

But now, as Brigadier General Edward J. Kendricks has noted in his introductory article to this report, flight has ventured into even loftier regions, where conditions begin to resemble those in space. At 50,000 feet, without pressurization, the lungs can no longer breathe any air, even if it contains pure oxygen. At 63,000 feet the total pressure is so small that body fluids will boil if they are exposed to it. And finally, at about 80,000 feet, it becomes impossible to pressurize the cabin with air from outside.

The reasons for this situation lie partly in engineering difficulties, partly in thermodynamic effects, and partly in toxicological troubles. The density of air at 80,000 feet is only about 1/30 what it is at sea level. To compress such rarified air with present-day pumps is technically prohibitive. They would be too heavy and too bulky.

Moreover, Mr. Alfred M. Mayo of Douglas Aircraft Corporation has pointed out that the mere process of compressing this air to a useful pressure would raise its temperature to about 400° Fahrenheit. Such heat would be intolerable for the occupants of the cabin.

Even if these drawbacks could be overcome, the ambient air itself is no longer fit to breathe. Between 60,000 and 140,000 feet

it contains ozone in considerable quantities. Ozone is a form of oxygen in which the molecule contains three atoms of that element, instead of two as in the air we normally breathe. It is formed at those high levels in the bombardment of ordinary oxygen by ultraviolet radiation from the sun.

More active than O_2 (oxygen), O_3 (ozone) is sometimes used in medicine as an antiseptic and a disinfectant. It has an irritating effect upon the delicate mucous membranes of the respiratory tract. In the amounts that would be present in ambient air, compressed to a useful range above 80,000 feet, O_3 would very likely have toxic effects.

Then, too, at still higher altitudes, other chemical reactions of a potentially harmful nature take place in the ambient air. The region between 100,000 and 200,000 feet is known as the chemosphere for that very reason. And, too, in wartime it is possible that an enemy might contaminate the ambient air drawn into a pressurized cabin at high altitudes.

For all these reasons, it becomes necessary at about 80,000 feet to replace the pressurized cabin with a new type of living unit, one that is pressurized from within. This cabin must provide all the physiological necessities of a habitable climate on the ground without any resort to the atmosphere outside. It must be closed off hermetically from that atmosphere, to prevent the escape of its precious air and to deny the entry of hostile elements from the environment around it.

Such a unit is called a sealed cabin. In practice, it would not necessarily be a single living space like most aircraft cabins today. Each passenger might be provided with his own tiny sealed cabin, either separately climatized or supplied with air from a central laboratory. The purpose of this design would be to confine the climatization to the smallest effective space. Also it would give each passenger his own protective cell for escape in case of an accident to the craft in flight.

A prototype of a sealed cabin, designed for research on the ground, is now in use at the Air Force School of Aviation Medicine. A metal cylinder resembling a small water tank or a furnace, its object is to study the environmental factors inside such a cabin in flights of several hours or days beyond the physiological limits of the atmosphere.

To provide a livable climate for this length of time, the sealed cabin must perform six or more vital functions ordinarily taken care of by the air around us and by the processes which the air sustains. First, it has to maintain a pressure which, near the ground, is supplied by the weight of the air itself. Then it must furnish oxygen as this gas is consumed by the occupants, and it must remove the carbon dioxide which they manufacture in the course of respiration.

Also it must take away, or reduce, the moisture which they give off both in breathing and in perspiring. It must keep down the temperature which is raised by body heat in a confined area as well as that heat caused by solar radiation and friction of the craft itself with the outside atmosphere. And it must control, as far as it can, the odors produced by the body in a confined area. The last of these functions is of some importance, if only for psychological reasons.

There are other problems in a sealed cabin, of a more or less routine character. One is the disposal of body wastes in flights of days' duration. Chemical means can be found to handle this matter. Another is to provide enough food and drinking water for the occupant. These are incidental problems in any vehicle designed for travel. The six we have listed, on the other hand, are specific to travel in a sealed cabin.

Suppose we consider these processes in a little more detail. The necessity for a substantial pressure of air on the body has already been discussed. It is secured by filling the chamber with a sufficient volume of air to produce that pressure. An ideal pressure would of course be that which we normally enjoy from sea level up to a mile or so above it. For structural reasons, however, it may be well not to have too great a pressure differential between the cabin air and the near-vacuum outside.

The lowest barometric pressure which the body would safely tolerate, without fear of the bends, might be about half the value at

sea level, or roughly 380 millimeters of mercury (Hg). This would be the pressure equivalent of an altitude of 18,000 feet, the greatest height at which human beings ordinarily work, in the mines of the Peruvian Andes. The oxygen pressure would need to be greater than it is at that altitude, unless the passengers were already acclimated to it, as the Andean Indians are.

It should be understood that these minimal pressures are proposed for military flyers in perfect physical condition. No such levels would be considered permissible for passengers in a commercial airliner flying at the same height. Airline pressures must be adjusted to the safety and comfort of elderly people, infants, and persons with various physical disabilities, such as mild cardiac or respiratory conditions. But in the next few years, at least, rocket flight at extreme altitudes will be confined to the Armed Forces.

A man performing the activities of a pilot uses about 0.9 cubic feet of oxygen each hour. Ordinarily he gets this from the enormous volume of oxygen in the air. But in the confined area of a sealed cabin he would have only what he took with him. Suppose the cabin provided 75 cubic feet of airspace per man, and started off with the normal pressure of 160 mm Hg at sea level. He would have about 16 cubic feet of oxygen, and would consume it at a rate of 5.7 per cent an hour.

Within six and a half hours the oxygen pressure in the cabin would drop to about 100 mm Hg. That is equivalent to an altitude of 10,000 feet, where the symptoms of oxygen deficiency generally begin. The oxygen pressure would have to be kept above this level. There is no formidable problem here, however, because fresh oxygen can easily be released from tanks. A standard cyclinder contains 240 cubic feet of compressed oxygen, enough to replenish one man's consumption for eleven days.

In a cabin pressurized for 18,000 feet, with an oxygen content equivalent to 12,000 feet, the proportion of oxygen in the air would be 26.3 per cent by volume, compared to about 21 per cent in the earth's atmosphere. The rest would consist of gases such as nitrogen, the chief constituent of ambient air, plus carbon dioxide and water vapor produced by the body. These are the components that would give us trouble.

Carbon dioxide (CO_2) is one of the end products of metabolism in the cells of the body. Water is another. Both are necessary to the tissue, but the excess must be removed continuously, or they become toxic. In the case of CO_2, we exhale about 0.7 cubic feet each hour. Normally this is dissipated in the air, where the carbon-dioxide pressure at sea level is only 0.23 mm Hg, or 1/33 of 1 per cent by volume.

After an hour and twenty minutes in a sealed cabin of the size we have been discussing, the CO_2 pressure will rise to 10 mm Hg, or 1.3 per cent of the air in the cabin. (In a cabin pressurized for 18,000 feet, the proportion will be higher, but the actual amount of the gas is of course the same.) Such a quantity of CO_2 in the air is considered the limit for human efficiency. Above 30 mm Hg it is definitely disturbing.

So the excess CO_2 must be removed from the air. There are certain chemicals with which this can be done, by absorption of the gas. A considerable amount of experience in the control of CO_2 in closed areas has been acquired by the Navy, in climatizing its submarines. A sealed cabin in space resembles a submarine in many respects.

Another way of removing CO_2 is now being studied. It is the process of photosynthesis in plants, which constantly extract this noxious element from our air. Vegetation reverses the metabolic system that maintains life in animals. It consumes carbon dioxide and water, producing oxygen and carbohydrates such as sugar. To perform this feat by photosynthesis, it requires sunlight and an enzyme known as chlorophyl.

The great advantage of this climatizing system in space flight would be that it exchanges CO_2 for O_2, the stuff on which human beings live. A small tree produces as much oxygen as one man consumes. Of course it would not be feasible to plant a small tree in a sealed cabin. But a mere five pounds of green algae, suspended in a nutrient solution, yield the same return.

This might be a practicable means of replacing carbon dioxide with oxygen on extended flights in interplanetary space. There the interesting situation would arise that a man returns less CO_2 to the air than the O_2 which he consumes. The difference is about 0.2 cubic feet an hour. Instead of providing additional oxygen for the crew, it might be necessary to carry extra carbon dioxide for the plants.

The drawback to this system is the light energy required. Either the entire mass of algae must be exposed in some way to the sun at all times, regardless of the attitude of the craft (and this would be possible only in interplanetary space, beyond the night-shadow of the earth), or an equivalent source of artificial light must be provided. In either case, the weight and bulk of the necessary equipment would seem to be prohibitive for a small craft. Still, this natural method of gas exchange is so attractive that it will be thoroughly explored.

The problem of moisture is similar to that of carbon dioxide. By evaporation from the body and exhalation from the lungs, we lose two or more ounces of water every hour. Over a period of several hours, in the inclosed area of a sealed cabin, this added moisture would increase the humidity in the air by a considerable amount.

At the same time, the body is producing heat as a result of its metabolic processes. In the course of moderate activity, the amount comes to about 100 gram calories per hour, or enough to raise an ounce of water nearly six degrees Fahrenheit in temperature. Added to the other factors tending to make the cabin hotter, the cumulative effect of this increase also is considerable.

The relationship between temperature and humidity is especially important. The hotter the air, the more moisture it can absorb. But increasing the humidity makes the heat more disturbing. We can be comfortable when the relative humidity ranges between 30 and 60 per cent, and the temperature from 50° to 75° F.

Moisture, like carbon dioxide, can be controlled by chemical or physical absorption. Heat is a more complicated question, particularly when the craft is moving through the lower levels of the atmosphere, where the denser air creates friction with its hull. At speeds between Mach 5 and Mach 10, which would not be exceptional for a rocket craft, the temperature of the air around it might reach as high as several thousand degrees.

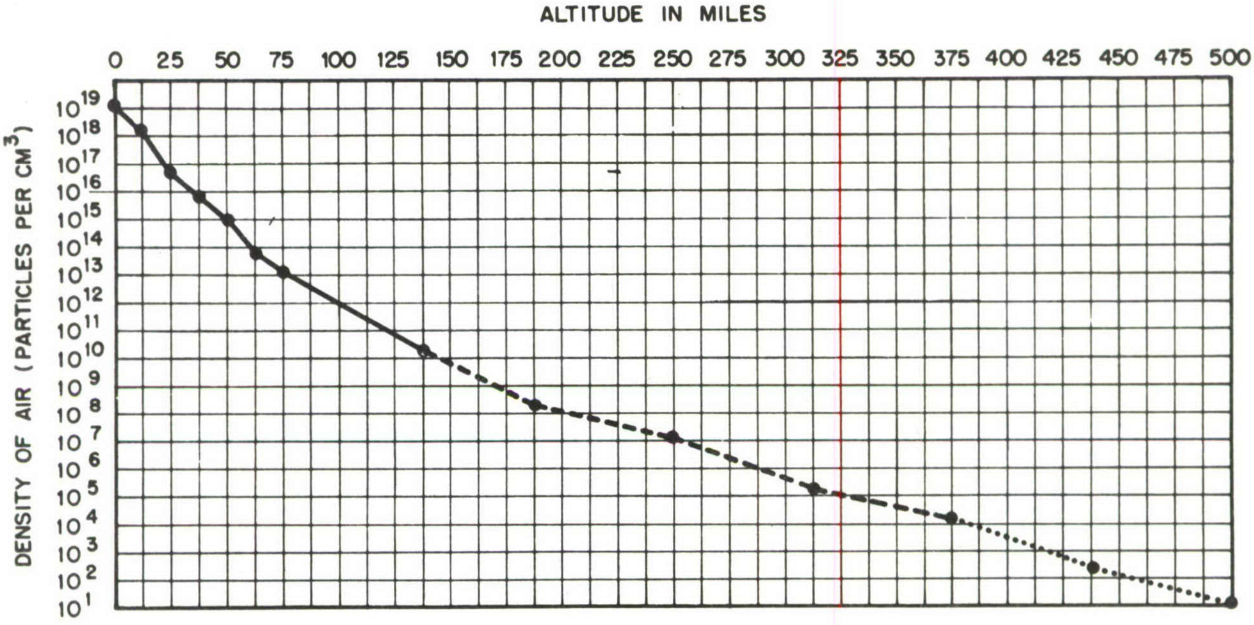
A certain amount of this heat would certainly be transferred through the hull to the cabin air. How much would depend upon the craft's construction, the density of the external air, and other factors. With present-day refrigerating equipment, the best we can expect is that the cabin temperature will be kept just within the limit of human tolerance.

Fortunately, the time during which a rocket craft passes through the denser layers of the atmosphere is brief. It does not attain its full speed until it enters a region where the density is so small that heat absorption through the hull becomes less important. Friction still makes the air hot. But the individual molecules are scattered so far apart that they transfer less total heat through the hull.

As the accompanying chart shows, the density of air decreases sharply up to 75 miles, or about 400,000 feet. At that point it is only one-millionth of its value at sea level. From then on it decreases more gently, until at the top of the atmosphere it is so tenuous as to become negligible.

The region above 120,000 feet, or about 23 miles, is where rocket craft may be expected to operate in the immediate future. There the density of air is only one-half of 1 per cent of what it is at sea level. Yet the number of molecules remaining in a single cubic inch of air is still more than 2×10^{18}, or 2 followed by eighteen zeros. Even though a molecule is infinitesimally small, this is a concentration sufficient to make the problem of heat transfer a serious one at that altitude.

Above 120 miles the number of particles per cubic inch is only 2×10^{11}. While this, too, is an impressive number of molecules, engineers consider that at this point they are so dispersed that heat transfer becomes inconsequential. An altitude of 120 miles, then, may be considered the thermodynamic border of the atmosphere. Beyond this level,



DENSITY OF AIR TO THE TOP OF THE EARTHS ATMOSPHERE

A logarithmic chart is used to show the rapid decrease of air density with altitude. Each line on the descending scale indicates a reduction to 1/10 of its previous value in the number of air particles per cubic centimeter. Data to 75 miles are from G. Grimminger, RAND Corporation. From 75 to 375 miles the calculation is by E.O. Hulburt, the broken line indicating extrapolation. The dotted line continues this extrapolation to 500 miles. Note that, from the ground to 75 miles, the decrease in density is sharp, averaging a reduction to 1/10 every 12.5 miles. From 75 miles to the top of the atmosphere, the decrease is more gentle, averaging a reduction to 1/10 every 35.4 miles.

the only external heat problem in a sealed cabin comes from solar radiation.

The heat which the sun pours upon the earth is generally measured by a term known as the solar constant. At the top of the atmosphere it amounts to 1.94 gram calories per minute on each square centimeter (0.155 square inches) of area. Radiation of this intensity on a square foot of surface will boil about 11 ounces of frozen water in one hour.

About half of this heat is absorbed by the atmosphere as it filters down to the ground, producing the various chemical reactions we have mentioned and the various phenomena of weather. The remaining half supplies the heat energy for all living processes on earth. The amount of heat radiation to which rockets are exposed at a height of 40 miles has been measured. It is approximately the same as the solar constant. Above this altitude, therefore, the sealed cabin receives the full intensity of the sun's radiation.

It has been calculated that this radiation can raise a hull of bright metal to a temperature of several hundred degrees, before an equilibrium is achieved between heat absorption and heat emission. By no means all of this heat, however, is felt inside the sealed cabin. A large part of it is reflected or absorbed by the material of the hull itself.

Moreover, the absorption of heat is only on the side of the craft which is exposed to the sun. The side that is in shadow radiates the heat of the craft into space. Hence, at such altitudes, the problem of retaining a physiological temperature within the cabin may be more important than the question of

heat absorption from radiation. A means must be provided to maintain a proper balance. At night, when there is no radiation from the sun and no blanket of warm air outside, the difficulty of retaining cabin heat could become tremendous.

Above 25 miles, too, we are exposed to another form of radiation which is constant, day or night, and which can penetrate the hull of the craft as if it were made of gauze or paper. This is the kind known as cosmic rays, because they apparently originate deep in intergalactic space. They traverse the vast reaches of the universe almost with the speed of light.

Primary cosmic rays, as they emerge from space, consist of subatomic particles. About 90 per cent are protons, or nuclei of hydrogen, the lightest element and by far the most abundant. Another 9 per cent are alpha particles, or nuclei of helium, the next lightest and most abundant. The remaining 1 per cent, however, are nuclei of heavier atoms, up to the weight of iron. Though small in number, these heavy primaries are extremely powerful.

When cosmic primaries encounter the atmosphere—or any other sort of matter, such as metal or living tissue—two types of reaction may take place. The penetrating particles may strip away electrons from the atoms in their path, leaving a trail of ions and electrons. This is a so-called ionization track. Or a particle may strike the nucleus of an atom. In such a collision the nucleus, heated instantly to billions of degrees, explodes into protons, electrons, neutrons, and other particles that fly apart at high speed in all directions.

In the atmosphere, these reactions occur at altitudes between 60,000 and 120,000 feet. The secondary cosmic rays resulting from the collisions are less potent than the primaries, having already dissipated much of their energy. They shower down through the lower layers of the air, still powerful enough to penetrate several hundred feet into water. Their effects, as we encounter them on the ground, are comparatively mild.

Above 25 miles we are exposed to the original cosmic primaries in their full force. If they pass through the hull of the craft without encountering another particle, they may strike deep into the body's tissues, leaving ionization tracks and exploded nuclei. The effects are much the same as the radiation damage from an atomic bomb.

Shielding the cabin's occupants against cosmic radiation may be impractical, because of the weight that any effective barrier would impose. Some natural shielding is provided by the earth itself, however, in flights not aimed at interplanetary space. Our planet acts as an effective barrier against half of the cosmic rays approaching from all sides in space. And in a geomagnetic band around the equator, reaching from 50° North to 50° South latitude, the intensity of cosmic radiation is relatively low. The particles have an affinity for the Polar regions. But the Polar regions, as it happens, lie across the shortest route to a potential enemy.

At the present time, space medicine is studying the biological effects of cosmic rays, the amounts that can be absorbed with safety, and possible means of protection against them. The incidence of heavy primaries fortunately is low enough so that the flyer may expect to find that he can stand exposures of several days or more at a time without danger.

It is unlikely that rocket craft will operrate very much above 25 miles in the next few years. When they do, they will face other difficulties of an unusual nature. The most spectacular is the prospect of a collision with a meteor. The size of such a flying mass of stone and metal might range from a small particle not much larger than a grain of sand up to a fragment weighing several pounds or more.

For the same reason that a rocket cannot cruise at great speed until it reaches an altitude above 75 miles, meteors are rarely seen very far below this height. They normally have a velocity ranging from Mach 45 to Mach 135 (12 to 36 miles per second) when they enter the atmosphere. In the relatively dense air between 75 and 25 miles above the ground most of them are vaporized. We see them only as light streaks on the sky.

Above 75 miles the rocket craft has no protection from the air. If a meteor strikes the hull, both the meteor and the hull at the

point of impact will be instantly vaporized. The size of the hole and the volume of air in the cabin will determine the speed with which the air escapes, and the time allotted the passengers to deal with the emergency. The problem then is that the sealed cabin is no longer sealed.

As in the case of cosmic radiation, the earth itself shields the craft from half of the sky's wandering meteors. The relative velocity of the meteor is governed partly by the motion of the earth around the sun, at a speed of 18.6 miles per second. When the meteor strikes head-on, its relative velocity is faster than if it overtakes the earth from the rear.

For this reason, between noon and midnight fewer meteors are seen than in the hours from midnight until noon; and meteors observed in the evening have a reddish glow, while those in the morning are bluish, because of the vastly greater heat produced as they vaporize. But the difference is of small comfort to a rocket passenger, because the velocity of the collision in either case is enormous.

Fortunately, the probability of a collision with a meteor is rather small, and the likelihood of colliding with one large enough to do formidable damage is smaller yet. Dr. Fred L. Whipple of Harvard University has suggested that a "meteor bumper" might be designed to guard the craft against these missiles. Consisting of a thin shell of metal outside the hull, with a space between them, it would vaporize the meteor before the hull itself could be damaged.

Still another problem of flight in the very high reaches of the atmosphere is the optical effect presented when air molecules no longer scatter the rays of visible light from the sun. The sky gradually darkens with increasing altitude, until at a height of about 75 miles it becomes totally black.

The darkness of space is more absolute than any seen on earth under the sky at night. It has the effect of a solid obstacle, like a screen, in which the stars appear as intensely brilliant points of light. The radiance of the sun is blinding as the glare of a gigantic searchlight turned on the voyager in space.

Any object on which sunlight falls through ports in a sealed cabin would be painfully bright—perhaps brighter than the eye could bear. On the other hand, objects in shadow would be very dark. The contrast itself would be a source of discomfort and confusion. The inside of the cabin—especially its instrument panel—almost certainly would have to be illuminated by artificial light.

So it is quite possible that passengers flying above 75 miles may never view the vastness which they have journeyed so far to see. It may be necessary to shut off any direct observation of the sky—or at least to cover the ports with light-diffusing panels, giving an effect as of ground glass—and to navigate entirely by instruments. Even fixes on stars may be taken entirely by electronic means.

In the cramped area of a cabin so drastically sealed, closed off even from visual contact with the universe, the flyer will have need of a singularly calm and stable temperament. The only comparable situation in man's experience is that of a submariner in an undersea vessel. Even there he is at most a few hundred feet below the surface, and surrounded by the teeming life from which he came. In a sealed rocket craft he will be many miles above his natural habitat, in a desolate region where no other living things are found.

The sealed cabin is, in fact, a miniature replica of the earth with its atmosphere inside—a tiny planet built as the habitation of a single man in space. Just as the rocket craft, in its motions, behaves like a cosmic body, so its interior climate must reproduce the atmospheric cloak which a habitable world carries with it. We cannot live in space without this protective medium around us. Wherever we go, it must go with us.

Up to the time when we can create a natural cycle of climatic conditions in the cabin, as on the earth, it will be necessary to return at frequent intervals to replenish the components in the air. So the sealed cabin cannot be considered a true space ship, though it may be a precursor of such a vehicle.

One day it may be possible to live for weeks or months or years in an artificial world of our own, while we travel among the

stars. For the present, all we hope to provide is a small, habitable cell, in which a man may be able to venture out for brief intervals to the lifeless solitude of space.

CHARACTERISTICS OF THE EARTH'S ATMOSPHERE

DOUGLAS AIRCRAFT COMPANY, INC.

A knowledge of the earth's atmospheric characteristics is important to air transportation as well as to weather prediction, radio communications, and the understanding of various phenomena that occur in our everyday lives. Realizing this importance, all branches of the physical sciences are exerting coordinated research to explore the earth's environment. Although there are many unsolved problems, the advances during the past decade in the state of our knowledge in this field have been outstanding.

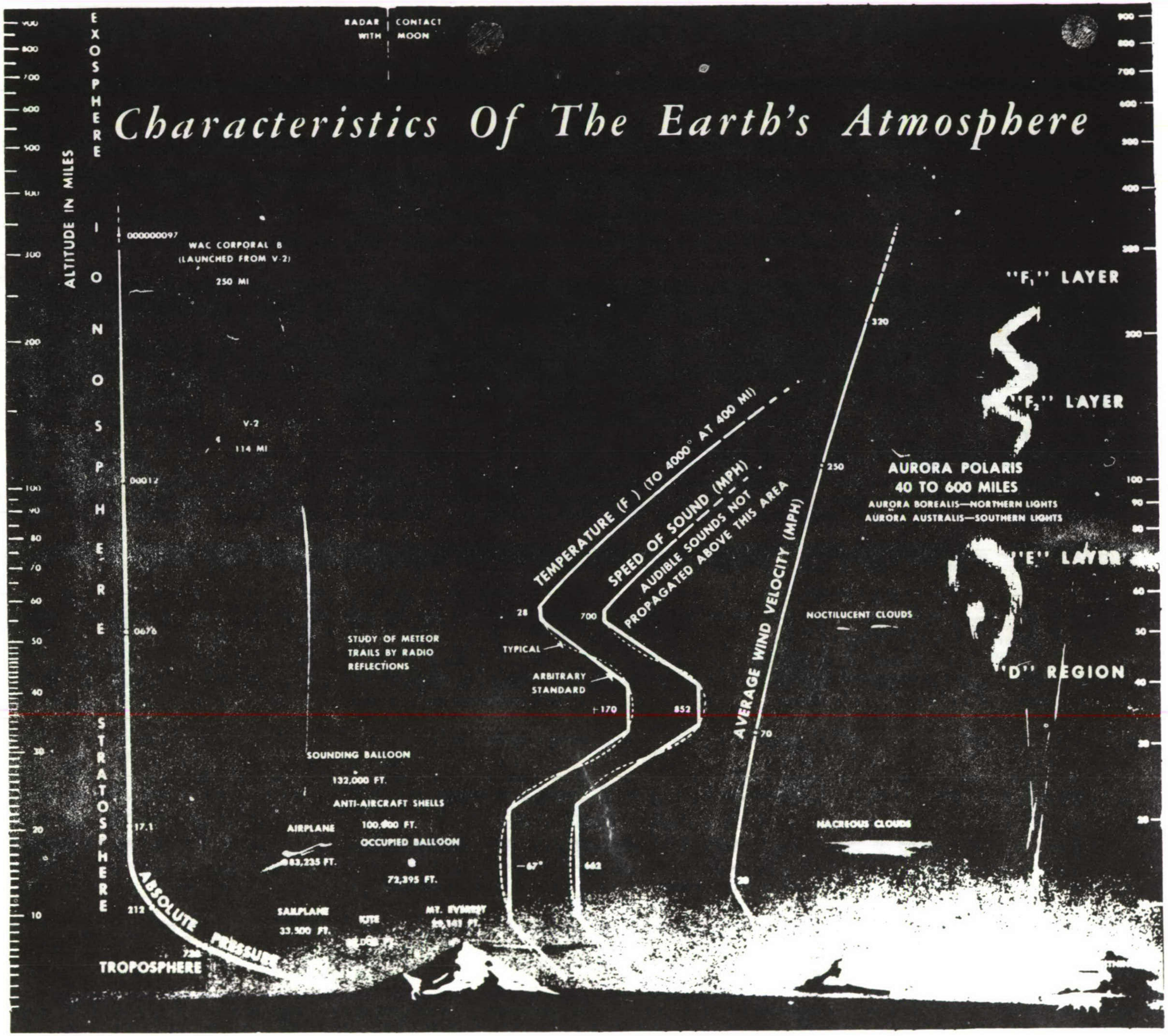
The earth's atmosphere is currently defined as consisting of four concentric gaseous layers; the troposphere, stratosphere, ionosphere, and exosphere. These layers provide a gradual transition from the atmospheric characteristics as we know them at sea level, to the exosphere which merges with interplanetary space. The weight of this atmosphere is approximately one-millionth of the weight of the earth, and a square foot column extending vertically through the atmosphere weighs approximately one ton. Of this atmospheric weight about 3/4 is concentrated in the troposphere, slightly less than 1/4 in the stratosphere, 1/3,000 in the ionosphere, and one-one hundred billionth in the exosphere.

Atmospheric characteristics vary with time of day, latitude and season of the year. Consequently, only representative average values are shown.

Levels: The earth's atmosphere consists of four concentric layers. Transition through these layers is gradual, without sharply defined boundaries. The first layer, the troposphere, extends from sea level to about 35,000 feet at middle latitudes, but varies from 54,000 feet at the equator, to 28,000 feet at the poles. This densest layer is composed of approximately 4/5ths molecular nitrogen and 1/5th molecular oxygen. The boundary between the troposphere and the stratosphere is called the tropopause. The stratosphere extends to an average altitude of 60 to 70 miles. In the upper portions of the stratosphere there exists a high temperature region (sometimes called the ozonosphere) caused by a concentration of ozone, which absorbs solar ultra-violet radiation. In composition, the stratosphere is similar to the troposphere. The ionosphere is characterized by free electrical charges. Some of the gaseous particles in this layer are broken down into ions and free electrons by absorption of the ultraviolet radiation from the sun, which also causes a dissociation of oxygen and nitrogen molecules into their atomic forms and causes very high temperatures. The outermost layer is called the exosphere or "fringe" layer. This region is occupied by gaseous particles whose motion is relatively unhampered by collision with each other.

Absolute Pressure: As distinguished from other characteristics of the earth's atmosphere, the vertical pressure distribution behaves in a regular manner and constantly decreases with increasing altitude.

The absolute pressure acting on each square foot in the earth's atmosphere at any given altitude is actually the weight of a square foot column of air from that altitude on outward. It is interesting that the increase in pressure only 34 feet beneath the surface of a lake is equivalent to the pressure developed by the entire height of the earth's atmosphere.



Characteristics Of The Earth's Atmosphere
ALTITUDE IN MILES
EXOSPHERE
IONOSPHERE
STRATOSPHERE
TROPOSPHERE
RADAR CONTACT WITH MOON
WAC CORPORAL B (LAUNCHED FROM V-2)
250 MI
V-2
114 MI
STUDY OF METEOR TRAILS BY RADIO REFLECTIONS
SOUNDING BALLOON
132,000 FT.
ANTI-AIRCRAFT SHELLS
AIRPLANE
100,000 FT.
OCCUPIED BALLOON
83,235 FT.
72,395 FT.
SAILPLANE
33,500 FT.
KITE
MT. EVEREST
ABSOLUTE PRESSURE
TEMPERATURE (F) (TO 4000° AT 400 MI)
SPEED OF SOUND (MPH)
AUDIBLE SOUNDS NOT PROPAGATED ABOVE THIS AREA
AVERAGE WIND VELOCITY (MPH)
TYPICAL
ARBITRARY STANDARD
"F1" LAYER
"F2" LAYER
AURORA POLARIS
40 TO 600 MILES
AURORA BOREALIS—NORTHERN LIGHTS
AURORA AUSTRALIS—SOUTHERN LIGHTS
"E" LAYER
NOCTILUCENT CLOUDS
"D" REGION
NACREOUS CLOUDS

Pressure falls rapidly at first with increasing altitude above the earth's surface. For example, at the top of Mt. Everest under standard atmospheric conditions, the atmospheric pressure has fallen to roughly 1/3 of the sea level value. At the outermost edge of the troposphere, the pressure has fallen to 1/4 of its sea level value. At the outermost limit of the stratosphere, pressure has fallen to 1/3,000th of the sea level value. From this point outward, the absolute pressures approach those of a complete vacuum.

The human body is affected by atmospheric pressure variation. Altitudes are indicated on the chart for which the blood and water vapor in the body will boil at normal body temperatures. "Bends" are likely to occur if the body is subjected to too rapidly changing pressure.

Man's Accomplishments: Man's efforts to explore the earth's atmosphere are exaggerated in the picture above. A more realistic picture is obtained by comparing the highest altitude achieved by man with respect to the earth's size and atmospheric depth shown to scale in the upper left hand corner. The greatest altitude attained by a man-inhabited vehicle until recently was 83,235 feet, over fifteen miles above the earth. This record was set on August 21, 1953, by a Douglas D-558-2 Skyrocket. Since then, the Bell X1-A has gone approximately one mile higher.

However, where man is not able to go himself, he has explored by other means. Developments in the field of radio communications have been invaluable aids in transmitting information from balloons and rockets, the latter having achieved an altitude of approximately 250 miles.

He has used radar to study the trails of meteorites and established contact with the moon; and radio has been used in studying the free electron layers of the ionosphere. Visual and spectrographic studies of the aurorae and lights of the night sky have been used to determine atmospheric composition to great altitudes.

As new and improved techniques are developed in the field of scientific research, man will extend his knowledge of the atmosphere to greater and greater heights.

Temperature and Speed of Sound: The temperature in the troposphere steadily decreases with increasing altitude. In the stratosphere, the temperature is at first constant, then increases to a maximum in the ozone layer. The temperature then starts to decrease again and reaches freezing temperatures just inside the ionosphere at the noctilucent cloud level. The temperature then increases through the ionosphere to reach its maximum constant value of about 4000° F. in the exosphere. The extremely high temperatures which exist at the upper altitudes do not have the same significance as the corresponding temperature at sea level. The temperature which a thermometer would read in this region would be determined more by solar radiation than by the temperature due to the energy of the particles, because of the extremely low particle density at these altitudes.

The speed of sound is proportional to the square root of the absolute temperature. However, as the distance between the molecules increases at the high altitudes, sound waves of the frequency corresponding to a piano scale are damped out in very short distances. The maximum altitude at which a given sound wave can be propagated increases as the sound wave length increases, i.e., lower notes on the musical scale.

Winds and Clouds: The atmospheric wind pattern is not understood in its entirety. The classical atmospheric circulation pattern of the trade winds is confined to the troposphere and is fairly well understood. In the stratosphere and ionosphere, however, there is evidence which shows that extremely high winds are present. The velocity and direction of these winds are known to vary with time of day and season and they are believed to be a part of the world wide circulation pattern. Study of the drift of noctilucent clouds and meteorite trails has been very useful in measuring the wind velocities at high altitudes. Extremely high vertical winds and turbulence in altitudes between 40 and 50 miles are indicated by the wavy form of the noctilucent clouds, and the results of theoretical calculations. These winds may prove to be a hazard to vehicles flying at these altitudes.

Cloud formations are probably the most commonplace evidence of the earth's atmospheric characteristics. Although most of the commonly observed clouds lie below the ten mile altitude, there are two rarer types, the nacreous and noctilucent clouds which achieve much greater heights.

Electrical Phenomena: Anyone who has witnessed lightning or auroral displays cannot help but be impressed with the extent of electrical phenomena within the earth's atmosphere. Auroral activity is limited to latitudes near the poles. Another visible electrical phenomenon is "light of the night sky," an emission similar to aurorae which accounts for two-fifths of the light in the sky on a clear, moonless night.

Non-visible electrical phenomena, such as the ionized layers of the ionosphere and the bombardment of the atmosphere by particles of vast energy such as cosmic rays, are also noticeable. Radiowaves near the broadcast frequency range are reflected back to the earth by the ionosphere. The structure of the ionosphere has been studied by measuring the reflections, absorptions, and time of travel of radio waves. These studies have identified four ionized layers whose intensity of ionization increases with increasing altitude. These layers are called the "D," "E," "F_1," and "F_2" layers. The layers of the ionosphere vary greatly in height and intensity; hence the differences in radio broadcast reception between night and day. Shorter waves, such as in television, and FM, penetrate the ionosphere to a greater degree and are generally not reflected back to the earth's surface at all.

FROM HIGH-ALTITUDE FLIGHT TO SPACE FLIGHT

HEINZ HABER, Ph. D.

INSTITUTE OF TRANSPORTATION AND TRAFFIC ENGINEERING
UNIVERSITY OF CALIFORNIA AT LOS ANGELES

The idea of conquering space in earnest is about thirty years old. The early space-flight enthusiasts were dreaming of extended travels to the moon and the nearest planets, while their small, make-shift rockets rarely surpassed a height of half a mile above the ground. In the following decades, however, the art of rocket propulsion was advanced to such a degree that all records of altitude and speed have been broken by rocket vehicles. Today we are approaching a point where far-reaching flights beyond the limits of the atmosphere must be considered the great challenge of the next fifty years of flight.

Unmanned missiles have been launched to a height of 250 miles above the ground, whereas the peak of a piloted rocket airplane lies at an altitude of about 17 miles. These figures sound modest if held against the tremendous spaces that separate the heavenly bodies: the distance to the moon is 240,000 miles, and it is more than a hundred times farther to the nearest planets. It looks as though there is still a long way to go; in particular it seems premature to worry about manned space flight at this time. But we would be grossly mistaken, if we would reckon the conquest of space by sheer distance. The atmosphere of the earth is only a thin film of air closely attached to the planet. Space flight must not be reckoned in terms of astronomical distances—it must be measured in the practical terms of how much of this atmosphere we leave behind in our present and future high-altitude flights. Three years ago the pilot of the famous "Skyrocket"—the Douglas 558-2—launched his craft to a height where less than four per cent of the earth's atmosphere

separated him from the emptiness of space. High-altitude flight will eventually become space flight as a natural result of our continued efforts to extend our vertical freedom of movement.

Will space flight become a reality during the next 50 years of flight? Nobody will expect a clear-cut answer to this question—all we can do at this time is to assess the difficulties and obstacles which as yet block the road into space and—what is equally important—the road back to earth. Rocket—and aircraft engineers agree that space flight will not be the result of a brand-new type of engineering; rather, it will eventually be realized as the result of the future development of rocketry and aviation combined. In other words—we will not be able to blast our way into space and retain enough fuel for a return to earth by using the recoil of the rocket engines to break the fall. The return to earth will have to be accomplished in gliding—coasting through the atmosphere in airplane fashion. In other words—we will have to learn how to fly an aircraft at any height by extending our present high-altitude flights to the very limits of our atmosphere.

Everybody knows that high-altitude and high-speed go together. This brings us to the problem of aerodynamic heating which presently looms at the horizon as an ultimate limit to airplane speed. In forcing its way through the air at high-speed, an aircraft acts like a piston inside a cylinder and compresses the air in front of itself. However, if air is compressed, it is heated up to considerable temperatures that threaten the structural stability of the craft. While this heating effect is most pronounced at the nose and the leading edges of the wings, the entire surface of the craft is heated by friction from the air. Several ways of avoiding the dangers of overheating suggest themselves: better structural materials which are more heat-resistant than the ones presently in use; elaborate cooling systems; and, of course, flying at greater altitudes where the air is thinner. The friction temperatures in the surrounding air produced by a speeding plane are not reduced at greater heights; but the thinner air contains less heat and also transfers less heat to the ship. The net result of these effects is that we can indeed fly faster and faster without running into the dangers of aerodynamic heating, if we only fly higher and higher.

Unfortunately this advice is not as easily followed as it is given. The problem involved was recently most succinctly stated by the author's brother, Dr. Fritz Haber. Take for instance a certain altitude—let us say 200,000 feet. Judging from present-day standards we can conclude that the maximum permissible speed at this height is about 5 Mach—five times faster than the speed of sound. Flying faster than this would produce so much aerodynamic heat that our aircraft would become too hot. However, at this altitude, the density of the air is more than 3,000 times lower than at sea level, and it takes a certain speed for the aircraft to derive enough aerodynamic lift from this vastly attenuated air. Using present-day wing-loadings as a standard, we find that we must fly with at least 10 Mach—ten times faster than the speed of sound—in order to remain airborne. We then have the choice between two alternatives: we can either fly at 10 Mach and burn up, or we can fly at 5 Mach and fall down. In the first case we are too hot, and in the second case we are too slow. Should we attempt to fly at 7.5 Mach, we are too hot *and* too slow. In other words—we can't fly at all at a height of 200,000 feet. In the present state of the art of flying, we can operate an aircraft in sustained flight only to a maximum altitude of about 100,000 feet. The conflicting conditions are resolved only at heights in excess of 400,000 feet, where the air becomes so thin that even a speed of 24 Mach would not produce aerodynamic heating great enough to become a danger for the ship. At this speed, however, aerodynamic lift is no longer necessary, because then the ship is supported against gravity by centrifugal force attending its fast motion around the earth. The ship has then become a satellite of the earth. Propulsion is only necessary to overcome what little friction is still present at this altitude. At still greater distances from the earth, all friction from the air would be done entirely, and the

ship could coast around the planet indefinitely without the necessity of being propelled. Meanwhile, however, the atmospheric regions between 100,000 and 400,000 feet appear to be unsuitable for sustained flight. It looks as though Mother Nature has failed to provide us with an atmosphere whose structure would permit us an easy escape into space and a thrifty return to earth. The engineering problems to be solved are obvious: better heat-resistant materials, smaller wing-loadings, and better aerodynamic configurations are necessary for extending our present high-altitude flights into new frontiers. It follows from these considerations that the realization of space flight hinges not only on the problem of adequate propulsion, but also on the problem of aerodynamic heating.

As high-altitude flight will eventually blend with actual space flight, we must also learn to protect the man in the rocket vehicle against the various hazards of space. The crew must, of course, sit in a pressurized cabin which preserves breathing oxygen at a physiologically adjusted pressure. The device of the pressurized cabin may not be enough. To forestall the acute dangers of sudden "explosive decompressions" in cases of cabin failure, the crew must be given added protection. In the spring of 1953 the U.S. Navy released to the public a new version of a pressure suit to be worn by aircrews in experimental airplane flights. This particular suit keeps the pilot encased in an air-tight shell that contains a breathable atmosphere of sufficient pressure. Although blown up stiff under operational conditions, this suit affords excellent mobility to its wearer. The suit could be worn on the surface of the moon or at any other point in space. It is the first version of a genuine space suit. There is hardly a better example than this suit, of how acute the problems of space medicine are even today.

In the years to come ever bolder and ever higher flights will be made. New problems of space medicine already appear at the horizon, since more and more factors of space environment will become effective as we progress. At a height of about 23 miles the concentration and nature of cosmic ray particles are the same as in actual space; the thin remains of air above this level are not sufficient to stop or transform these rays from space to any perceptible degree. Before longer flights above this region will be made, we must know more about the possible dangers of this unearthly kind of radiation. There are reasons to believe that cosmic radiation will not be a forbidding obstacle to brief flights through "space"; but we are not yet equipped to pronounce space radiation-safe for long periods of exposure.

At still greater heights the atmosphere will no longer protect us against meteoric hits. The bulk of meteors is absorbed by the air within the layer between 65 and 95 miles of altitude. At about the same level, the air becomes so thin that the heat exchange between the ship's outer hull and the air around comes to an end. The temperature of the craft will then be determined by exchange of radiation between the craft's exterior and the sun. Control of temperature can be effected by a proper choice of paint. A metallic surface gets very hot under the impact of solar radiation as proven by the temperatures of window sills of cars that are parked in the sun. Only gleaming white surfaces stay cool in space.

During a coasting flight outside the mechanically effective layers of the atmosphere the crew of a rocket aircraft or space ship will become weightless. In the absence of the disturbing forces of propulsion and air drag, the ship will travel along a celestial orbit in which the force of gravity is precisely cancelled by forces of inertia. The result is weightlessness of men and things alike. Before actual space flight will be achieved, weightlessness lasting up to about six minutes will be experienced by crews of rocket aircraft. Since the state of weightlessness is a rather unique and disturbing condition, it is the task of space medicine to study this problem before our flight operations can be extended to ever increasing heights and speeds.

Before the first man may dare venture into space, a great number of engineering and medical problems will have to be solved. Although the difficulties look formidable,

nobody is equipped to say at this time that they cannot be overcome in one way or another during the next 50 years of aviation development. The question then arises as to what benefits may accrue from an eventual successful conquest of space. To the adventurous mind, craving for new frontiers, this question may not make much sense; many contend that space must be conquered because "it is there." It is true, man's insatiable curiosity about the things around him has been playing a decisive role in the history of this Planet's exploration and conquest. But these feats of the past were accomplished by relatively simple and inexpensive means. One small sea-going sailing ship and a courageous mind sufficed to bring the American continent into the orbit of Western man. It will take billions of dollars and thousands of skilled minds and hands to reach our closest neighbors in space—the moon, and the planets Venus and Mars. However, upon closer inspection these heavenly bodies reveal their generally uninviting nature, each in his own way: the airless moon, the hot Venus, and the arid Mars. Our neighbors in space are hardly worthwhile objects of exploitation. For a long time to come, an interplanetary expedition cannot be expected to yield economic returns great enough to justify the huge expenditures involved.

But the realization of space flight in the shape of the artificial satellite may well turn out to be an extremely profitable investment of our future efforts in the field of aviation. Coasting around the earth permanently at close distance, such a platform in space would be an ideal vantage point from which the entire planet and its atmosphere could be observed and studied continuously. This would permit us to advance the sciences of meteorology and climatology to such an extent that we could even hope to eventually control the atmosphere for the benefit of all mankind. Hurricanes, disastrous droughts and floods could be accurately forecast, diminished or even averted. The artificial satellite could eventually be used to survey gigantic global projects designed to change the climate of whole sections of continents to the better. The satellite would be an indispensable tool in an age of "planetary engineering."

The future of aviation seems to hold a great promise: flight can become more than a means of locomotion and transportation—it could also become an important tool for future tasks of engineering our planet into the best possible shape.

THE PECULIAR STATE OF WEIGHTLESSNESS

SIEGFRIED J. GERATHEWOHL, Ph. D.

DEPARTMENT OF OPHTHALMOLOGY
USAF SCHOOL OF AVIATION MEDICINE

Of all the strange sensations that men may soon encounter in sustained rocket flight, the strangest is the condition of zero-gravity, in which they will have no feeling of weight. It is psychologically the most fascinating problem of space flight, because it has no parallel in human experience on the ground or in most conventional flying. It is the most difficult to investigate, because it can be produced only in circumstances approximating those of actual flight in space.

At first glance, it might seem that weightlessness would be a very simple, pleasant experience—rather like floating through the air as we do sometimes in dreams, or like drifting on the surface of a pool of water. But this is not necessarily the case. On earth we are never free from weight. The dream condition is only a wish fulfillment

which in itself recognizes the consciousness of weight. The swimmer is still subjected to the full force of gravity, but is supported on the water as he would be on a solid object like a bed.

Actual weightlessness can be experienced only when the force of gravity itself is removed—or, to be more specific, when it is counter-balanced by an opposite force. Then no gravitational pull whatever acts upon the body's organs. The result is a condition which may seriously affect the flyer's behavior and his orientation—that is, his ability to locate his position in space by his own subjective feelings and perceptions.

In such a state the directions which we call "down" and "up" cease to have any meaning. The automatic compensation of the muscles for the body's normal weight produces erratic and exaggerated movements. And there is a possibility that the mind's response to this eerie situation might be one of befuddlement and uneasiness, if not of actual terror.

The phenomenon which we know as weight is the result of the gravitational tug of the earth's mass, drawing us toward its center. We are only aware of the force because of the support provided by the earth's surface—or, in an aircraft, by the lift of the wings—that prevents us from falling freely. If the support is removed, and we do fall freely, then there is no longer any sensation of weight. But this never happens in the lower regions of the earth's atmosphere, up to an altitude of about twenty miles, because the resistance of the air itself provides a substantial measure of support.

It has been calculated that a body falling through the lower atmosphere cannot attain a greater speed than about 90 knots. But, in a free fall in space, the body is constantly accelerated. Without any mechanical restraint, the only force that could be opposed to gravitation is the body's own inertia. However, its inertia responds freely to gravitation, and so the body is weightless. No one has yet bailed out of a craft above 100,000 feet, and so no one has ever been subjected to a free fall in the full sense of the term.

Another case of weightlessness, or zero gravity, is provided when a body moves in a so-called Keplerian trajectory. This is the kind of arc whose most familiar examples are the orbit of celestial objects like the Moon or the earth itself. The speed of the body then creates a centrifugal force that exactly balances the pull of the gravitational field through which it moves, and the body has no weight. It may be thought of as falling freely through space, but in a curving path that never brings it downward toward the center of the mass that attracts it.

Such a trajectory need not be confined to the outer reaches of space. A craft with sufficient speed could fly a Keplerian orbit a few feet off the ground. And a jet plane a few miles up can fly an arc in such a way that for a number of seconds, it follows a Keplerian trajectory. In this case, thrust counteracts drag and centrifugal force counterbalances gravity, so that for a time the plane and its occupants are weightless.

In jets, because of their limitations in speed and altitude, zero gravity can be achieved for only about 30 to 45 seconds. But with rocket propulsion the situation is quite different. After a relatively high initial acceleration, the rocket attains such velocity that it can coast for the rest of its flight, without any additional power except possibly in landing. By this means, after the rocket has penetrated the bulk of the atmosphere, it cruises entirely unsupported by the forces of lift that sustain conventional aircraft.

In this cruising state, both the missile and the passengers become weightless, and remain so until they reenter the denser air below. Thus it can be said that weightlessness is the normal gravitational condition in rocket flight, whether we speak of the relatively brief ascents that may be made before long for tactical and observational purposes, or of the prolonged flights that may some day be made into outer space.

It is important to realize that this condition has nothing to do with the craft's distance from the earth, except to the extent that distance affects the density of the air. Weightlessness is simply a function of speed and trajectory, produced by the equilibrium of gravity and centrifugal force. In

practice, it can occur anywhere outside the atmosphere, or within it if the craft is properly flown along a parabolic course.

A German professor, Dr. Heinz von Diringshofen, first observed the phenomenon of weightlessness during World War II in experimental flights. Just after the War, Drs. Otto Gauer and Heinz Haber, then performing research at the Aeromedical Center in Heidelberg, Germany, noted the rapid advance of rocketry and drew some hypothetical conclusions about the effects of zero gravity on the flyer's mind and body.

Briefly, they postulated that the brain receives its information on the position, direction, and support of the body from four perceptual mechanisms: pressure on the nerves and organs, muscle tone, posture, and the labyrinth of the inner ear, which contains a number of small, calcareous particles called otoliths that indicate changes in acceleration and direction by exerting pressure on their hair cells. Drs. Gauer and Haber theorized that the first three of these mechanisms would cease to function properly when weight is removed from the body, and that the otiliths might send signals to the brain which would actually confuse the rocket traveler.

The possibility was serious enough to convince several investigators for the United States Air Force that some means should be found to study the effects of weightlessness under experimental conditions. In June 1951, Dr. Heinz Haber and his brother, Dr. Fritz Haber, both of whom had by then joined the Department of Space Medicine at the USAF School of Aviation Medicine, published a paper in the *Journal of Aviation Medicine* on "Possible Methods of Producing the Gravity-Free State for Medical Research." They recommended flying a Keplerian trajectory as the only practicable method. Later Dr. Heinz Haber joined this author in a discussion of the "Physics and Psychophysics of Weightlessness," also published in the *Journal of Aviation Medicine.*

In 1951, at Edwards Air Force Base, California, the noted test pilot, Scott Crossfield, made fifty flights in an F-84, following Keplerian trajectories, for the National Advisory Committee on Aeronautics. About thirty of these flights produced zero-gravity conditions for 15 to 40 seconds. The results were inconclusive in some respects. Crossfield reported a feeling of "befuddlement" during the transition into weightlessness, but this feeling disappeared after the fifth flight. He had no sensation of falling, and no loss of muscular coordination other than a tendency to overreach with his arm. He did experience some vertigo occasionally on the pullout after a run.

Crossfield himself conceded that true zero gravity might not have been attained, because in almost every flight considerable drag was felt, indicating a longitudinal deceleration during the trajectory. The pilot of course was strapped to his seat, and had no lack of visual references to compensate for any tendency to disorientation. The period of weightlessness was perhaps too brief to establish any definitive findings.

Similar flights were made at about the same time by Maj. Charles E. Yeager at Edwards Air Force Base and by Dr. E.R. Ballinger with the cooperation of the Fighter Test Branch at Wright-Patterson Air Force Base, Ohio. Dr. Ballinger's observations coincided with Mr. Crossfield's. His subjects expressed the opinion that, if they had not been restrained by seat belts and had been blindfolded, "disorientation might been extreme." Major Yeager experienced a brief sensation of falling in the transition to the weightless phase. Also he noted some orientational difficulty, which was later described as follows by Dr. Heinz Haber:

"In his thirteenth second of weightlessness, he got the impression that he was spinning around slowly in no particularly defined direction. After 15 seconds he became lost in space, and he pulled out of the parabola. With returning weight, his badly-needed orientation was restored too." Still, these subjective impressions did not fully confirm or deny the possibility of physiological and psychological disturbances with the prolonged removal of gravity.

A group of researchers, headed by Dr. James P. Henry of the Aero Medical Labora-

tory at Wright-Patterson Air Force Base, then attacked the problem in a different way. They sent mice up in three test-rocket launchings, with cameras to record their behavior during weightlessness. A V-2 and two Aerobees were used in these experiments.

In the first test, with the V-2, a single animal was carried in a small compartment with a wire-mesh floor. Still photographs were taken at four-second intervals throughout the flight. It was difficult to analyze the subject's reactions by this technique. Signs of disorientation were observed, but the mouse was able to maintain his coordination by clinging to the wire mesh. During the weightless phase, he appeared as comfortable in an inverted position as in any other.

In the later studies, with the Aerobees, cylindrical drums were placed in the rockets, rotating laterally about their axes. Motion pictures were taken during the weightless period of two to three minutes, and again as parachutes braked the rocket's descent, restoring normal weight. In each test the drum was divided by a smooth plexiglas wall into two compartments, with an animal in each, for comparison.

Both compartments in the first Aerobee were equipped with small hurdles, over which the mice had to jump in order to remain on the "bottom" of the drum. The floor of the drum was smooth. One of the animals was normal; the other had lost the labyrinths of the ear, with their directional otoliths.

The normal mouse was much confused by the removal of weight, clutching desperately for some kind of foothold as he floated freely in the compartment. The labyrinthectomized mouse was less disturbed. He received no clues, either true or false, from the otoliths, and was accustomed to his lack of orientation.

In the second Aerobee both mice were normal, but only one was provided with a hurdle on the floor of the rotating drum. This animal clung to the barrier and managed to keep some kind of equilibrium. The other moved violently about the compartment, not only confused by the loss of weight but also seemingly unable to adjust his muscular tension to the small amount of effort required for motion.

Another striking series of animal studies was reported recently by Dr. H.J.A. von Beckh in the *Journal of Aviation Medicine*. For some time Dr. von Beckh has been studying orientation and coordination with a species of South American water turtles. They are particularly suitable for research of this kind, because they move in three dimensions in the water. Ordinarily they strike with deadly accuracy at their food, projecting their long, S-shaped necks like snakes toward the target.

Dr. von Beckh went away for a few days, leaving a caretaker to watch over his laboratory. He returned to find that the water in the turtles' tank was far above a tolerable temperature. Several of the animals were dead. One had lost the use of his labyrinth, which is the main organ of orientation in turtles, as in human beings.

For several weeks the injured turtle was unable to coordinate his movements properly. In striking for his food, he would miss the bait, and had to be hand-fed. Then the animal learned to compensate for the damage to his otoliths by visual orientation. Presently he was as adept as the other turtles in seizing a bait.

At this point Dr. von Beckh placed several of the animals, including the injured one, in a small, open tank, and took them up in a fast two-seater aircraft. He put the plane into a series of dives, securing brief periods of zero gravity. During these periods he tested the coordination of the animals.

One difficulty in the dives was that the water, with the turtles in it, would rise up out of the tank and float above it. Several times it was necessary to lift the tank and fit in around the water again. This was a graphic demonstration of the physical effect of weightlessness.

As von Beckh had expected, the damaged animal was able to snap at his food without trouble during these weightless moments, using the visual cues that he had learned. The normal animals behaved as the turtle with the useless labyrinths had behaved immediately after his accident. In the course of some twenty or thirty flights, however, they too began to regain their coordination.

Von Beckh also did a group of experiments in flight with human subjects. In these he was associated with Dr. von Diringshofen, who first raised the question of the effects of weightlessness in Germany, and who had gone to the Argentine after the War. The subjects were required to draw crosses in seven small squares arranged diagonally across a sheet of paper. The tests were made during weightlessness, sometimes with the eyes open and sometimes when they were closed.

Extreme difficulty was exhibited by the subjects in drawing the crosses under zero-gravity conditions. When their eyes were shut, they lost all sense of orientation. However, as with the turtles, after a considerable number of flights their accuracy improved.

Von Beckh has pointed out another effect of weightlessness that applies in tactical evolutions with conventional planes. He had the pilot dive from about 10,000 to 7,000 feet and pull out rather abruptly, afterwards rising on the ascending arc of a parabola. In this maneuver, after an acceleration of about 6.5-g, the pilot found that his blackout lasted longer, his responses were delayed, and he had the sensation of flying upside down.

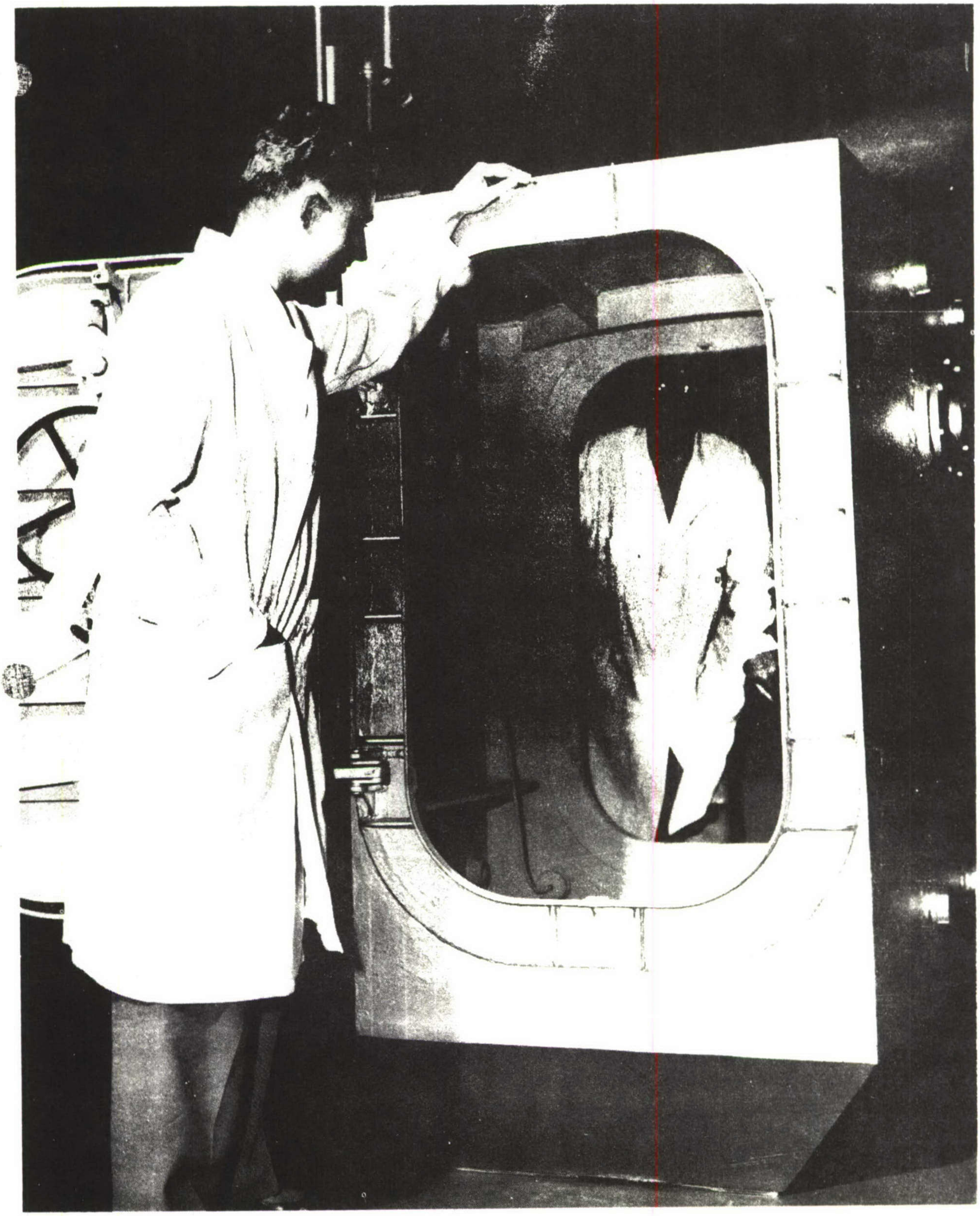
Situations of this kind may occur in aerial combat, when fighters dive on a bomber from above, pull up to make the gunnery pass from below, and then dive again to evade the bomber's fire. In such maneuvers the flyer may experience a few moments of weightlessness after high acceleration at the critical point of the attack. The result may be to impair his vision and coordination when he needs them most.

These preliminary studies—all covering weightless conditions of short duration—seem to show that there is a definite tendency to disorientation in a flyer when normal gravity is removed. On the other hand, it appears that the effects can be overcome in time by an experienced pilot, especially if he can fall back on visual points of reference.

In the rocket craft of tomorrow he may have fewer such reference points. Because of the intense and confusing contrasts between light and darkness at very high altitudes, because of the craft's tremendous velocity, and because of the need to shield the flyer against various types of radiation, it may be necessary to close the cabin altogether and to fly solely by instruments. As every pilot knows, instrument flight lends itself more readily than VFR to orientational disturbances.

Beyond that, we have to ask ourselves what may be the effects of a prolonged period of weightlessness, lasting from several minutes to several hours or more. Difficulties which are readily overcome in a few moments of intense concentration may develop subtler and more serious manifestations over an extended time of comparative idleness.

In weightlessness we face a condition which man has never experienced before. We have no precedents on which to predict its effects, and no means of producing it artificially for experimental purposes on the ground. We know that the sensation will be novel and perhaps weird, but we cannot determine in advance just how the psychological symptoms will reveal themselves. We can only explore the subject cautiously as the science of rocket flight advances, and hope that the lifting of this age-old burden from men's bodies will not raise problems so extreme as to incapacitate them.



PRODUCING THE WEIGHTLESS STATE IN JET AIRCRAFT

SIEGFRIED J. GERATHEWOHL, Ph. D.*
OSCAR L. RITTER, Ph. D.†
HERBERT D. STALLINGS, Jr., Major, USAF‡

**Department of Ophthalmology*
†Department of Radiobiology
‡Flight Operations

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Air University

SCHOOL OF AVIATION MEDICINE, USAF
RANDOLPH AFB, TEXAS

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Some simple arithmetic functions were used for computing duration, height, and angle of climb of flight parabolas for producing the weightless state in jet aircraft. The results, based upon certain flying characteristics of the T-33, F-94, and F-104, are in good agreement with the data obtained for the first two types of aircraft mentioned during actual zero-gravity maneuvers. Certain flying safety hazards were noticed in the T-33 but remedied through appropriate measures. The F-94C Starfire proved to be superior to the T-33 with regard to safety and duration of weightlessness obtained. If the F-104 were made available for aeromedical research, weightlessness could be produced for more than 1 minute.

In studies of human behavior under conditions of virtual weightlessness, the reduction or elimination of gravity has become an important problem of aeromedical research (1, 2, 3). The following means have been suggested or employed for producing the weightless state: the use of an elevator, the "gravitron," the "subgravity tower," and the aircraft, or the dropping of a capsule from an airplane (4, 5, 8). However, only the use of aircraft seems to be practical because of its availability, its safety, and the longer periods and various amounts of reduced gravity that can be produced in it; moreover, the state of weightlessness obtained is more realistic than that produced in other ways.

In order to appreciate the use of modern aircraft for accomplishing the weightless or "agravic" state, one must understand some of the mechanical principles of gravity and acceleration. As expressed in Newton's Universal Law of Gravitation, all bodies exert mutual forces of attraction upon one another. In accelerated motion, gravity is the vectorial sum of the forces of gravitation and inertia acting on a body. According to the Newtonian relation

$$F = m \cdot a \qquad (1)$$

the force of gravity is measured most conveniently in terms of acceleration; with the acceleration due to the terrestrial gravitation $g = 32.17$ ft./sec.[2] as the unit. Normally, when an object is in a state of rest, the forces of inertia are absent; the object is, therefore, in the "normal state of gravity," expressed as $G = 1$ (1).

Allowed to fall freely, a body is subjected to a downward acceleration of 1 g. In this case, the forces of inertia compensate the forces of gravity, putting the body in a state of "zero gravity" (6). If the body is subjected to a downward acceleration of less than 1 g, the forces of inertia are subtracted from the gravitational force. In this case, the body is in a subgravity state. In both cases, a second force is superimposed upon the force of gravitation (7).

Within the gravisphere of the earth a body derives its weight from the counterforce that resists its free fall. On the other hand, a body can be defined as weightless if it is allowed to move freely under the influence of gravitation and its inertia only.[1] This is the case when the object is moving along a Keplerian trajectory. According to the d'Alembert principle, every body—whether accelerated or not—finds itself in a state of equilibrium under the combined effects of the actual forces exerted on it—that is, forces of gravity, forces of inertia, and external forces like propulsion, lift, drag, and support. Equation 1 thus may be written:

$$F - m \cdot a = 0. \qquad (2)$$

Now, since F represents the gravitational

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[1] Although the terms *zero gravity* and *weightlessness* designate the same condition, *zero gravity* is used here to refer to the physical state, and *weightlessness*, to the psychophysiologic experience of the individual.

forces and $m \cdot a$ the "reactive effects," we write

$$F_g - F_r = O \tag{3}$$

where F_r represents the reactive forces—that is, the inertial effect associated with the acceleration of gravity. In the free-fall situation in a vacuum, F_r is a quantity equal in magnitude and opposite in direction to F_g, and can be identified as the sole effect of inertia. When an airplane flies along a Keplerian trajectory, F_r represents the inertial and external forces superimposed on F_g. In other words, the aircraft then simulates the motion of a missile cruising in a vacuum. In order to obtain lack of appression in flight through air, the craft must be guided along a parabolic arc, thereby utilizing the inertial forces for counterbalancing F_g.

A flight maneuver of this type requires the elimination of all accelerations except the one caused by gravitation, which constantly acts downward at a magnitude of 1 g. The pilot can accomplish this by flying the plane through a so-called push-over, holding the needle of his accelerometer precisely between plus and minus 1 g at the zero mark of the instrument. A push-over is a vertical-planar maneuver in which the angle of climb changes continuously from a plus to a minus value. During the maneuver the airspeed decreases uniformly from an initial value v_o to a minimum at the top of the curve, and then increases uniformly back to the initial value shortly before the pull-out. However, the horizontal component of the velocity remains constant during the entire maneuver. It is determined by the minimum speed at which the aircraft is fully controllable and stable during the push-over. Hence, the horizontal component of velocity or "minimum controlling speed" of the airplane is always somewhat higher than the stalling speed. It depends mainly upon the amount and arrangement of control-surface area built into the aircraft.

Throughout the maneuver, the plane moves at considerable airspeed. Therefore, a power output of the engines ranging from an appreciable fraction to full power must be maintained to overcome drag although no lift is required. This holds for the downward as well as the upward leg of the maneuver.

The characteristics of the trajectory described above reveal that it is a parabola with vertical axis. Strictly speaking, the intended trajectory is one described by an unpropelled body in ideally frictionless space subjected to a centrally symmetric gravitational field. Generally, such a trajectory is a conic, one focal point of which always coincides with the center of attraction around which the body revolves. For sufficiently small velocities, such as are achievable by present-day aircraft, the conic is a very elongated ellipse with one focal point at the center of the earth. The small section near the apex of the ellipse, emerging from surface of the earth, can well be represented by a parabola. The condition for good approximation is that the dimensions of the section are small compared to the radius of the earth or, alternately, that the part of earth surface arched over by the section can be considered as flat instead of spherical.

It should be emphasized that the flight path is not necessarily parabolic or elliptic if a state of reduced rather than zero gravity is intended. In this case, the characteristics of the trajectory are determined by additional requirements concerning the direction of the resulting subgravity force with respect to the aircraft. If, for instance, the force is to be directed perpendicularly toward normally positioned seats regardless of the instantaneous orientation of the plane, one obtains a rather complicated functional form of the flight profile which resembles a parabola only superficially (4). On the other hand, if the subgravity is to be directed vertically toward the surface of the earth irrespective of the orientation of the plane, the resulting trajectory is always parabolic.

For the mathematical analysis of a parabolic flight pattern, an orthogonal coordinate system can be employed having a horizontal x-axis and a vertical y-axis. The angle of climb is determined by the direction of the aircraft at the beginning of the appressionless state—that is, at the point O in figure 1. The interesting and important information to be obtained from an analysis of the flight parabola concerns the duration of the weightless state and its dependency upon other flight parameters.

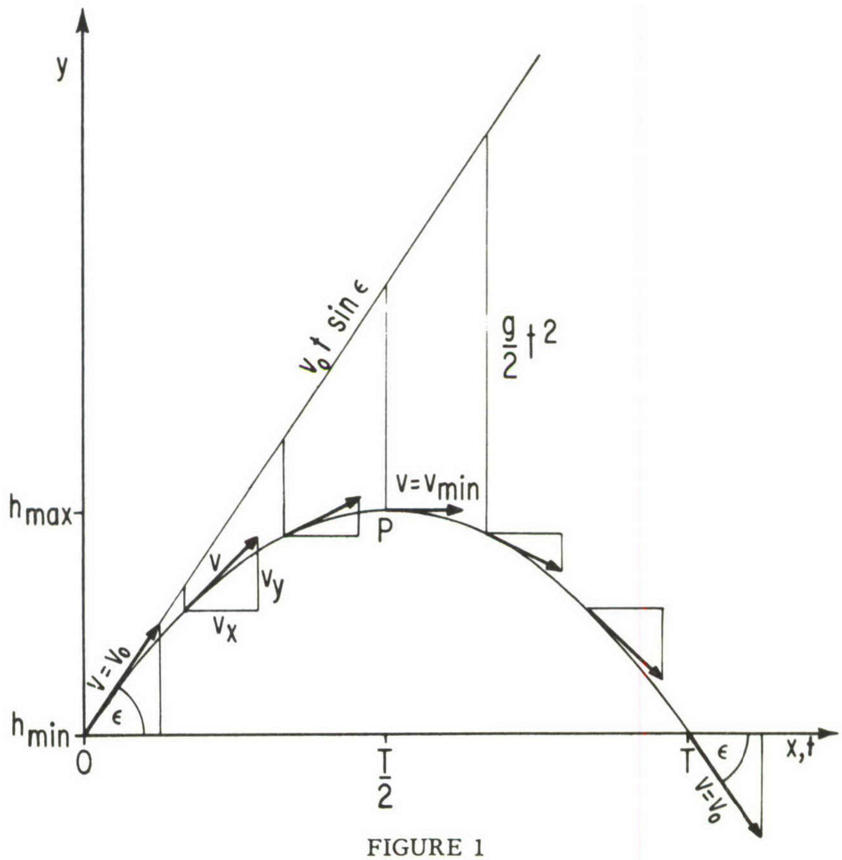

FIGURE 1

Schematic of parabolic arc. In the absence of gravity, a craft starting from point O at an angle ϵ would follow the straight line $v_0 t \sin \epsilon$. Gravity causes the craft to fall. The vertical line segments between the straight line and the parabola represent the height of fall at the corresponding points of the trajectory. Also shown are directions and relative magnitudes of the velocity and its horizontal and vertical components. The velocity reaches its minimum at the peak P of the parabola where the vertical component vanishes. The magnitudes of the speed at begin and end of the parabolic are equal. The same holds for the angles ϵ.

In ballistics, the duration of the trajectory is defined as the time required for the projectile to again reach the level of its initial projection. In the flight pattern described in this paper, T is the duration of the weightless state. From figure 1 it can be seen that the vertical location of any point of the parabola can be expressed by:

$$y = v_0 t \sin \epsilon - \frac{g}{2} t^2; \tag{4}$$

where v_0 = the initial velocity of the aircraft, and ϵ = the initial angle of climb. In order to find the duration of the flight, we determine the value t for which y again becomes 0:

$$T = \frac{2}{g} v_0 \sin \epsilon. \tag{5}$$

Equation 5 shows that T depends upon the value of g, the velocity v_0, and the angle of climb ϵ, the latter two quantities measured at the point O. At a given v_0 the longest duration is obtained when ϵ = 90 degrees—that is, when the projectile is propelled straight up. However, the airplane cannot rotate about 180 degrees at zero speed on top of a straight-line ascent, nor can it maneuver safely below or at its stalling speed. For reasons of good maneuverability we have to stay within the limitations of

our flight pattern—that is, the controllability on the one hand, and the maximum permissible velocity shortly before pull-out, on the other. The controllability speed is always somewhat higher than the stalling speed of the aircraft and can be determined by flight tests. In a similar manner, the maximum permissible speed is not utilized in parabolic maneuvers but v_o instead, which is the airspeed available by the excess thrust for propelling the aircraft upward from the preceding pull-out. If an object is hurled upward with a certain initial velocity v_o it will, neglecting air friction, rise to its maximum height in the same time it takes to fall from that height to the ground. The same principle is true for the parabolic maneuver in which case, then, the speed at the end of the trajectory also equals v_o. Hence, our problem is reduced to finding the optimal value of ϵ with respect to the initial velocity v_o and the minimum maneuvering or controllability speed v_{min} of the airplane.

The optimal angle of climb can be found by considering the velocity diagram at point P in figure 1. Since the horizontal component of the velocity must be constant through the entire maneuver, v_x is of the same magnitude as v_{min}. Thus we write:

$$v_x = v_{min} = v_o \cos \epsilon, \tag{6}$$

$$\cos \epsilon = \frac{v_{min}}{v_o} \quad . \tag{7}$$

Equation 7 shows that the optimal angle of climb depends upon the ratio of excess thrust and minimum controllability speed.

Finally, we want to know what relationship exists between the duration of the weightless state and the peak altitude of the maneuver. The maximum height h_{max} is defined as the greatest vertical distance reached by the aircraft as measured from the ground. In figure 1 the maximum height is that of the peak P of the parabola:

$$h_{max} = h_{min} + \frac{v_o^2}{2g} \sin^2 \epsilon. \tag{8}$$

Another simple representation results if the peak of the parabola is chosen as origin of the coordinate system. In this system, the altitude at any time is

$$y = h_{max} - \frac{g}{2} t^2, \tag{9}$$

and the downward vertical component of the velocity is

$$v_y = gt. \tag{10}$$

From the total velocity

$$v = \sqrt{v_x^2 + g^2 t^2} \tag{11}$$

the duration of one leg of the parabola is found

$$\frac{T}{2} = \frac{1}{g} \sqrt{v_o^2 + v_x^2} \tag{12}$$

where

$$v_{oy} = \sqrt{v_o^2 - v_x^2} \tag{13}$$

is the vertical component of the velocity at the end points of the parabola. In terms of maximal and minimal altitudes, this vertical component and the total duration can be represented by

$$v_{oy} = \sqrt{2g(h_{max} - h_{min})} \tag{14}$$

$$T = \sqrt{\frac{8}{g}(h_{max} - h_{min})}. \tag{15}$$

Finally, the optimal angle of climb is again given by formula 7.

Table I gives characteristics of the flight path by which weightlessness of maximum duration can be produced, using three different types of airplanes currently available in the United States. The data concerning minimum controllability speed, entry and pull-out speed, and operational altitude, which served for the computation of the optimal angle of climb, peak altitude, and duration of the weightless state, were obtained through parabolic flights involving states of decreased or entirely abolished appression. Table I shows that longer periods of weightlessness can be produced when higher performance aircraft are employed. In figures 2, 3, and 4, the total duration T of the maneuver, the height $h_{max} - h_{min}$ of the parabolic arc, and the optimal angle of climb ϵ_{opt} are given in the range of maximal speeds between

TABLE I

Characteristics of optimal flight parabola for three different aircraft

Aircraft	Minimum controllability speed	Entry speed v_o	Starting altitude	Maximum height over ground	Angle of climb	Duration of virtual weightlessness (sec.)
	(knots)		(feet)			
T-33A	180	320	18,000	20,600	55°	28
F-94C	195	425	18,000	24,400	63½°	40
F-104B	200	800	40,000	66,800	75½°	82

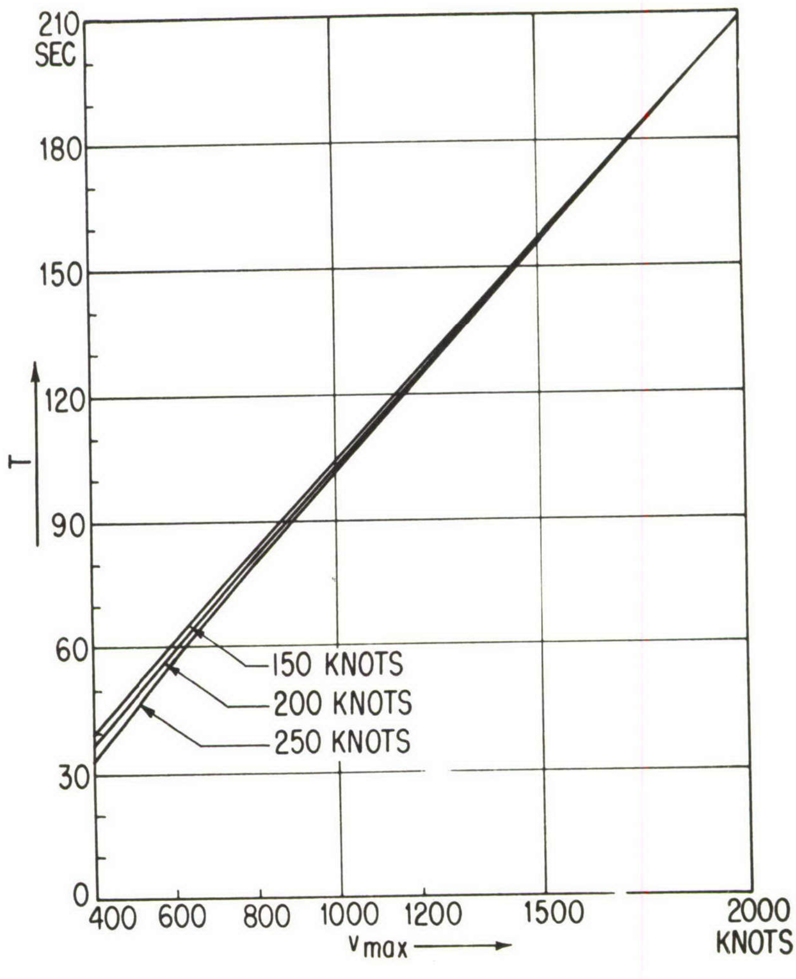

FIGURE 2

Duration T of parabolic maneuver in relation to maximal and minimal speed. The duration is approximately proportional to the maximal speed the craft can achieve. The minimal controllable speed has little influence unless it amounts to an appreciable fraction of the maximal speed.

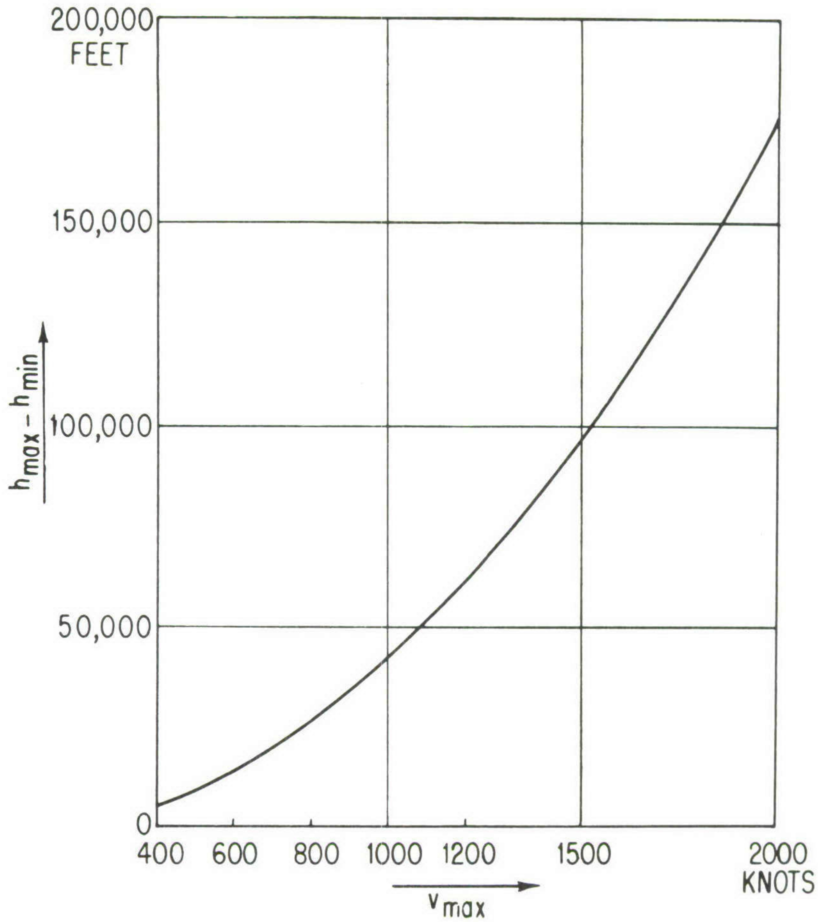

FIGURE 3

Height of the parabolic arc vs. maximal speed, for a minimal speed of 200 knots. The height increases approximately with the square of the maximal speed. For minimal speeds of 150 and 250 knots, the curve is shifted up or down, respectively, by approximately 1,000 feet.

400 and 2,000 knots for three values of the minimal speed.

Prominent test and research pilots such as Major (Chuck) Yeager, Major Arthur Murray, Scott Crossfield, Bill Bridgeman, and Captain Iven Kincheloe—just to mention a few—have on several occasions experienced weightlessness, but little has been published concerning the practical realization of this state. Information already available needs to be disseminated, however, as more research organizations become involved in the problem of fact-finding. Now, having had the opportunity to try it ourselves and having accomplished more than 200 parabolic flights in the T-33 and F-94 type aircraft (encompassing a total of about 2,000 individual parabolas), we feel encouraged to present our practical experiences to the interested organizations and individuals. The presentation will also show how the practical results agree with the figures given in table I.

Since jet fighters are in great demand by many research units of the U. S. Air Force, preliminary investigation was not begun until 1955 when the School of Aviation Medicine, USAF, was assigned a Lockheed T-33A type jet aircraft powered by a J-33A-35 engine developing 4,600 lb. thrust. Inasmuch as we had no information to work with, it was agreed that the exact flight patterns and working altitudes would have to be determined by a trial-and-error method. Numerous flights were made using different altitudes,

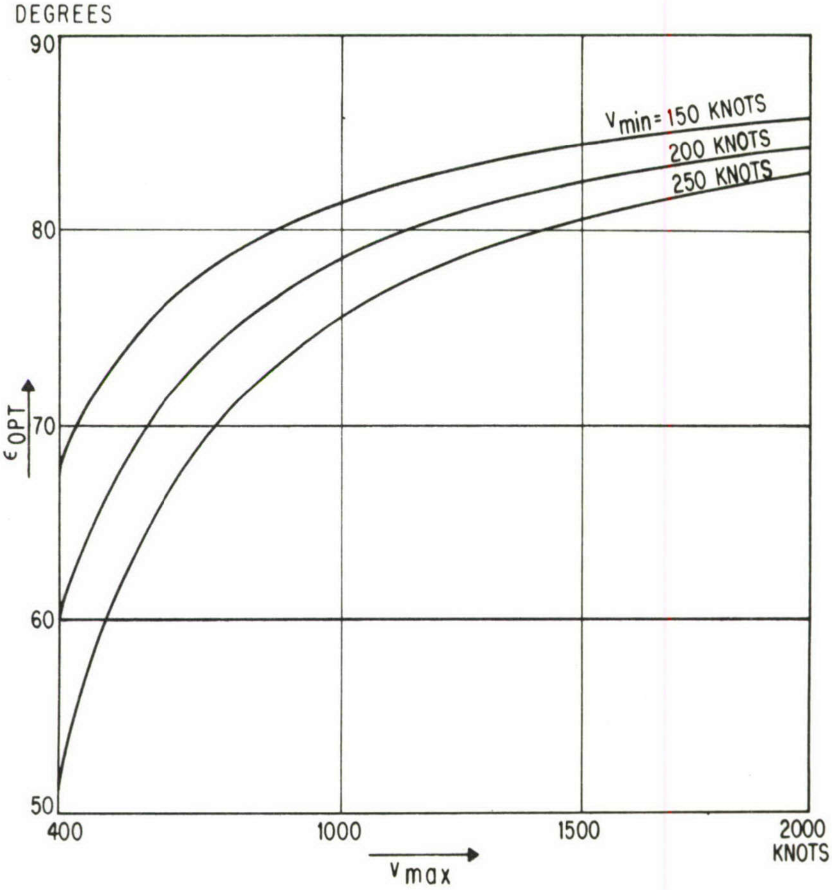

FIGURE 4

Optimal value of the initial angle of climb in relation to maximal and minimal speed. The optimal angle steepens with increasing maximal speed and approaches 90 degrees for very high speeds.

entry airspeeds, angles of attack, and power settings. From the data gathered, the most acceptable flight pattern was selected: Although attempts were made at altitudes that varied from 10,000 to 30,000 feet, the best starting altitude was found to be about 20,000 feet. This altitude, therefore, was considered the optimum working altitude because of usual lack of clouds and turbulence at this height, and because this altitude provided the requirements of safety in the event of emergency. At this altitude the parabola can be flown, utilizing the maximum performance of this particular aircraft with the maximum amount of safety; that is, in case of engine trouble, we could, at this level, effect corrective action that would enable us either to return to the base or to eject successfully.

At 20,000 feet, a sharp dive was started at 96 percent engine r.p.m. As the indicated airspeed (IAS) built up to 350 knots, an altitude of 17,500 feet was usually reached. Now, a sharp pull-out was begun, resulting in a positive 3 G condition, and the aircraft was put into an angle of climb of about 60 degrees from the horizontal at full throttle. As the IAS dropped off to 300 knots, forward pressure was applied to the control stick and thus the push-over initiated. At this point of the maneuver, a slight and momentary yawing of the aircraft occurred but it was easily controlled by aileron movements. Slight changes in forward pressure were also required to control the attitude of the plane and to maintain the zero-gravity state.

Airspeed at the top of the parabola was about 180 knots, and altitude ranged from 20,000 to 20,500 feet. As the apex was reached, forward stick pressure was continued until the plane was diving at an

IAS of 350 knots. When the angle of dive was approximately 75 degrees, a pull-out was started early enough to prevent the aircraft from passing its Mach limit and avoiding an excessive radial acceleration during recovery. Usually at this point, the maneuver was repeated, again using the pull-out speed for the upswing into the next parabola. (See fig. 5.)

Theoretically, the IAS is not an important factor for producing the weightless state; in actual flying, however, it is of utmost importance. Yaw and roll movements of the T-33 during parabolas produced undesirable accelerations in all three axes owing to the sensitive aileron boost at low air speeds and rolling motions exaggerated by tip fuel. This was not the case in the F-94C which was used in later experiments.

The standard g-meter installed in all U. S. Air Force fighter aircraft was employed as a primary reference. Furthermore, the weightless state was indicated by the release of some small object, usually a cigarette lighter, a glove, or in several instances a flashlight in the cockpit. When the object was stationary or floated in space before the observer's eyes, there was little doubt that zero gravity was present. The parabolic arcs obtained in this fashion varied from 25 to 28 seconds; the actual state of zero gravity lasted for a few seconds only, but the gravitational force was drastically reduced for the rest of the time. For this reason, we call the entire condition the state of virtual weightlessness.

These T-33 flights were not without incident, however. During the subgravity state at altitude, fuel in the main tank tended to vaporize, resulting in an overflow from the tank out through the vent drain line. This vaporization prevented the fuel pump from supplying enough fuel to the engine to maintain the required engine r.p.m. Fuel pressure was constantly observed during the run, and as soon as a reduction occurred, the parabola was discontinued and application of positive G's usually brought engine operation back to normal. The few power reductions that occurred during zero gravity were corrected immediately by reducing throttle and applying positive G-forces. Complete loss of oil pressure also took place but was of little concern because of the known ability of this engine to run long periods with no lubrication whatever. The aircraft's hydraulic system was unaffected.

As the experiments progressed it was felt that extended parabolas were necessary in order that future research concerning man's reaction to zero gravity could be successfully continued. Since the T-33's capabilities had been exploited to their limits, and since the power loss that had repeatedly occurred during

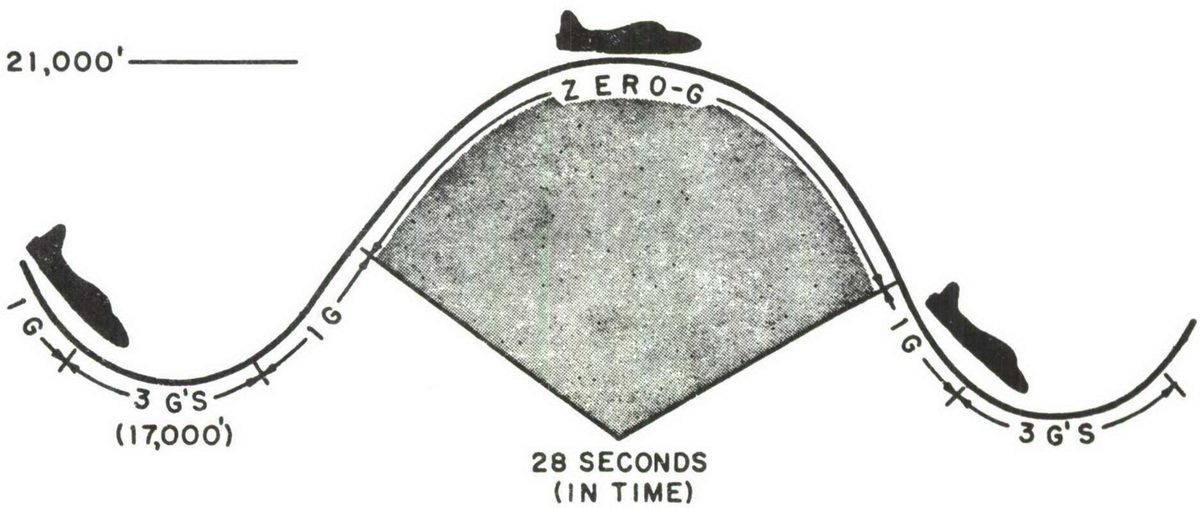

FIGURE 5

T-33 "zero-g" flight pattern. The maneuver starts at an altitude of about 18,000 feet, reaches almost 21,000 feet at the top of the parabola, and yields about 28 seconds of virtual weightlessness.

flight was certainly not consistent with safe aircraft operation, a request was forwarded to Headquarters, United States Air Force, for assignment of a two-place jet fighter capable of high thrust and high Mach performance with a pressurized fuel system, to be used in the study of weightlessness. In May 1956, an F-94C Starfire was assigned for this purpose.

Once again various patterns were attempted using different entry air speeds and altitudes. For the same reasons as with the T-33, the most satisfying altitude was about 20,000 feet. A dive was entered, engine r.p.m. at 100 percent, and as the IAS reached 425 knots a climb of 65 to 70 degrees from the horizontal was executed. With airspeed dropping off, forward stick pressure produced a stable and lengthy parabola yielding almost 40 seconds of practical weightlessness. Since the F-94C has a pressurized fuel system, the treacherous power loss was absent and the 6 degree dihedral present in the Starfire's short but able wings produced a parabola free of rock and roll that had made the T-33 hard to control. The F-94C's variable elevator boost made small aft and forward control changes both easy and instantaneous, allowing small corrections to be made without varying the G-conditions appreciably. The high Mach rating eliminated the necessity of a too early dive recovery. In short, this ship now performed with both a high degree of efficiency and safety so necessary in our experimental flights (see fig. 6).

The afterburner of the Starfire was also used to produce the longest period of weightlessness ever recorded—namely, 43 seconds. In this maneuver at 20,000 feet with elevator boost ratio at 11:1, engine r.p.m. was increased to 100 percent and the afterburner actuated. IAS was increased to 430 knots, and the aircraft eased up into a climb of 75 degrees from the horizontal. The afterburner was used until this angle was reached in order to obtain an IAS of somewhat over 400 knots. At that time the afterburner was cut off and the parabola begun. Because of the high rate of fuel consumption, the afterburner was not used thereafter unless an extended period of weightlessness was required.

Since we still lack an accurate instrument for indicating and recording sub- and zero gravity, and the conventional g-meter registers accelerations in the vertical only, an auxiliary indicator of G-forces in the three axes was introduced. A golf ball, painted black and white for better visual reference, was

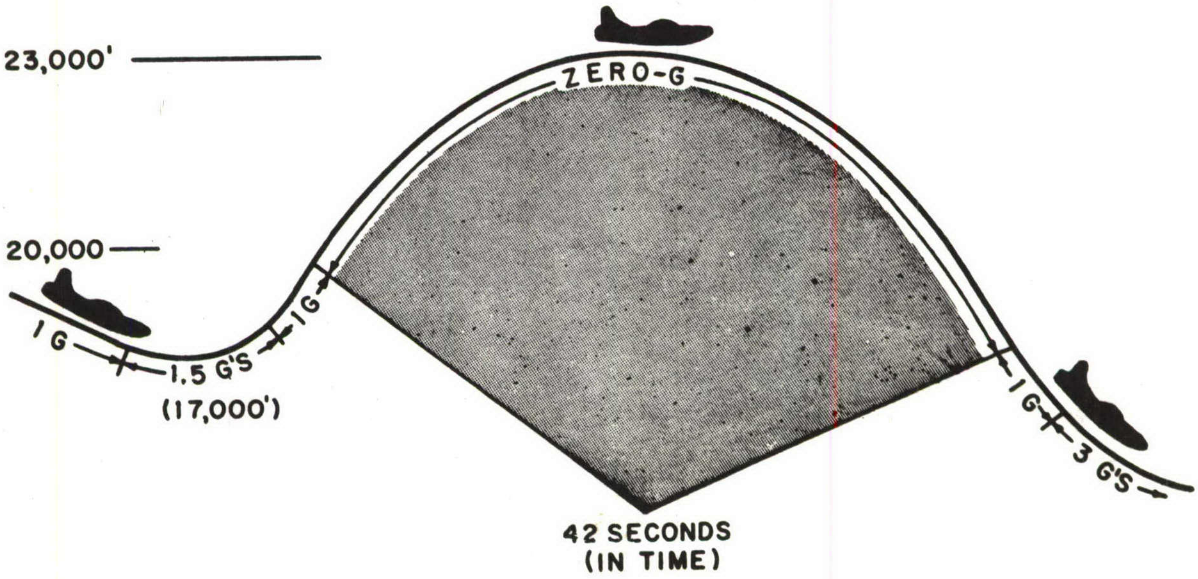

FIGURE 6

F-94C "zero-g" flight pattern. The maneuver is started at an altitude of about 18,000 feet, reaches about 23,000 feet at the top of the parabola, and yields about 40 seconds of virtual weightlessness.

fastened to the end of a 14-inch length of nylon cord. This contrivance was hung in the center top of the windshield inside the pilot's portion of the cockpit. Entry into the zero state was determined by the conventional device. Then, as weightlessness was achieved, the pilot tapped the ball slightly from below, lifting it just enough to allow it to float. This primitive but revealing device portrayed any acceleration in the three space axes by moving in the opposite direction of its inertia. Through practice, these movements could be kept at a minimum, and corrections were made by the pilot by simply "flying the ball" so to speak. Moreover, a zero-accelerograph was installed in the F-94C to register the vertically and longitudinally acting accelerations within the range of ± 0.5 g during the weightless phase.

Both parabola patterns, described with the T-33 and the F-94C, had their advantages and their shortcomings. The first one, with the sharp dive, produces longer states of weightlessness after preceding states of markedly increased acceleration. The second one, with the shallow dive before being practically weightless, yields a shorter zero-state, but the preceding acceleration of 1.25 g generally remains unnoticed because of the slow rate of change. Hence, the second maneuver seems to be appropriate for determining the effects of weightlessness on the body without preceding increase of weight, which also affects the human organism. The pilot has flown all zero-gravity research flights at the School of Aviation Medicine, USAF, and—assuming an accumulated weightlessness of about 3 minutes during each flight—has been weightless for almost 11 hours with no apparent untoward effects. However, this figure does not mean too much because of the short periods of exposure during each individual parabola.

SUMMARY AND CONCLUSIONS

Simple functions were used for computing the most interesting and important characteristics of parabolic flights. The results, based upon certain flying characteristics of the T-33, F-94C, and F-104 in subsonic and transonic flight, are in good agreement with the data obtained for the first two aircraft types during actual zero-gravity maneuvers. Certain flying safety hazards were noticed in the T-33 but remedied through appropriate measures. The F-94C Starfire proved to be superior to the T-33 with regard to safety and duration of the weightless state. If the F-104 were made available for aeromedical research, weightlessness could be produced for almost 1½ minutes.

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THE AERO MEDICAL PROBLEMS OF SPACE TRAVEL

by

H.G. Armstrong, Heinz Haber, and H. Strughold

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HEADQUARTERS
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Aero Medical Problems of Space Travel

Panel Meeting, School of Aviation Medicine

General Harry Armstrong, *Chairman*, Dr. Heinz Haber and Dr. Hubertus Strughold

General Harry Armstrong

THE TOPIC for the panel is "Aeromedical Problems of Space Travel." Space is defined as:

> "That which is characterized by extension in all direction, boundlessness, and indefinite divisibility; that in which all physical things are ordered and related at one time; the subject of determinations of position and direction. According to this, space is boundless, but not infinite, in extent, and a ray of light traveling a sufficiently long time, estimated by Einstein as 500 billion years, would return to its starting point."

I would like to say a word about the selection of the subject for this panel discussion. It was agreed upon by a representative of the National Research Council, the director of the Aero Medical Research Laboratory at Wright Field, a representative of the Air Surgeon's Office, and representatives of the staff of the School of Aviation Medicine. We sought a topic which would be timely, of general interest, and one which would lend itself to discussion by individuals qualified in the different fields of medicine and the basic medical sciences. During our deliberations, I happened to mention that six months previously I had asked two of the scientists at the school to collect the data in the open literature on conditions in the atmosphere at variable distances from the earth's surface which would cause medical difficulties if one were exposed to those conditions. These two gentlemen had just about completed their review of the literature, and it was thought by all present that this topic would make a very timely and realistic problem for the panel.

At the present time, rockets are being sent to considerable heights, and it would be of great advantage if they could be manned. Thus, we are not contemplating something in the indefinite future but a problem which exists today and will increase in importance as time goes on.

Dr. Heinz Haber, astrophysicist of the School of Aviation Medicine, and Dr. Hubertus Strughold will outline very briefly, and in a rather general way, the problems they have uncovered from a review of the literature and will then discuss in some detail one or two specific points.

Dr. Heinz Haber

The greatest difficulty to be encountered in possible future interplanetary travel is the accumulation of an adequate energy supply which would enable a space ship to overcome the gravitational field of celestial bodies, particularly that of the earth. It is generally agreed that the necessary amount of energy can hardly be procured by chemical fuels, unless extremely unfavorable ratios between fuel amount and payload are tolerated. Yet, atomic energy, in its utilization for rocket-type power plants, has not reached the stage of perfection which would make

it applicable for the solution of interplanetary travel.

The problems concerning the human factor of space travel will become most urgent if a suitable propulsion becomes available; it can easily be concluded that the physiological part will play a more decisive role in the initial stages of space travel than it did during the early stages of aviation. The future-minded aeromedical science, therefore, must concern itself with an anticipation of medical problems in relation to the possibility of interplanetary travel. Interplanetary travel will create a close relation between two sciences hitherto unaware of each other: astronomy and medicine. We cannot afford to postpone a close collaboration between medical men and astronomers any longer. Medicine may find it profitable to adopt a principle generally practiced in astronomy: astronomers have a habit of working for the future, for their grand-children. Due to this habit, we today are in possession of observations which were gathered by our forefathers and left for our benefit as very fine specimens of pure scientific curiosity. In the same way, future medical science will take advantage of efforts made at present. Obviously, it is worth our while to concern ourselves with this somewhat futuristic problem.

As has been pointed out before, chemical fuels do not quite fulfill the requirements for an energy supply of a space ship. So, this discussion will be based on the assumption that a source of energy is available which is about ten times as efficient as the best chemical fuels to date.

If we are going to shoot a body away from the earth, finally enabling it to travel through space, we have to accelerate it along a radius of the earth, for instance. If the propulsion is shut off too early, the body will fall back. In other words, a critical velocity must be attained which will enable the body to break free from the gravitational pull of the earth. A body having been accelerated to or beyond this critical speed will continue to rise even without propulsion, yet with decreasing velocity. However, before the velocity relative to the earth has become zero, the body will be subjected to the composite gravitational fields of the bodies of the solar system, particularly to that of the sun; then the body will describe a Keplerian orbit whose elements are determined by direction and size of its velocity and by the combined gravitational pull of the celestial bodies. No further propulsion is required in order to keep the body traveling.

This critical velocity mentioned before is called escape velocity. For our home planet the escape velocity amounts to 11.2 kilometers per second. This is a figure large enough to bother the engineer as much as the physiologist. Unfortunately, in the important and critical procedure of take-off and landing, the principles of rocket engineering run counter to the interest of the physiologist. The task of the physiologist is to protect the interplanetary navigator from harm, whereas the engineer regards economy of the energy consumption as the essence of his task. This divergence is due to the fact that the fuel consumption decreases decisively with increasing acceleration of the ship. It is for this reason that a successful attempt to

overcome the earth's gravitational field can likely be accomplished only with an energy source more efficient than those available to date. Yet, research on the influence of gravitational forces on man indicates that one will be able to reckon with this difficulty as far as its physiological part is concerned. The physiologist will be interested to know how long man—in order to attain the escape velocity—must be subjected to accelerations higher than 1 g. Disregarding the friction of the air in the first phase of the take-off procedure, the correlation between the acceleration applied and the time required can easily be computed. Table I shows this correlation for some rates of acceleration computed for a launching from above the atmosphere.

TABLE I

Acceleration Physiologically Effective	Duration of Acceleration
3	9 min. 31 sec.
4	6 min. 21 sec.
5	4 min. 45 sec.
6	3 min. 48 sec.
7	3 min. 10 sec.
10	2 min. 6 sec.

This is the order of values the physiologist will have to deal with, provided the engineer does not limit the physiologist's choice any further.

As mentioned before, the space ship, once liberated from the earth's immediate gravitational field, will be carried further through space along a Keplerian orbit. The ship then must be considered as a celestial body, equal in rank to planets, moons, and comets. These bodies are in an ideal equilibrium between the gravitational forces exerted upon them by other bodies, chiefly the sun, and the forces owing to their proper inertia. This means, physically, that the component of all forces of gravitation and inertia is exactly zero, since the gravitation due to the ship's own little mass will be almost immeasurably small. It means physiologically that the ever-present stimulus of gravity is absent; this condition subjects man to a state unexperienced before. Only during a small fraction of time can this condition be realized within the earth's atmosphere—at the instant after a man has jumped from a diving board, for example, as long as friction of the air is small enough not to impede his body from falling freely at the exact rate of the law of free fall. Disregarding friction, the aforementioned ideal equilibrium exists during this small period of time.

As soon as a change of the ship's orbit becomes necessary, the rocket propulsion must be started again; in this case the ideal equilibrium will be disturbed, resulting in forces which are experienced as "gravity" by the navigators. Their orientation will be restored immediately, and they will sense the direction of the rocket exhaust as being "down."

Regarding these facts, the physiologist will be interested to know how long the interplanetary navigator must be subjected to the gravity-free state, in order to reach our moon and the neighbor planets, Mars and Venus.

A rather simple consideration will enable us to estimate the length of time required for a journey to neighboring celestial bodies. The speed of a space ship on a trip to the moon will be of the order of the home planet's parabolic velocity (11.2 km. per sec.); on the average, however, it will be somewhat lower, because, if circling

the moon, the space ship must enter into the moon's range of influence. It will be possible for the ship to be caught by the moon's gravitational field, only

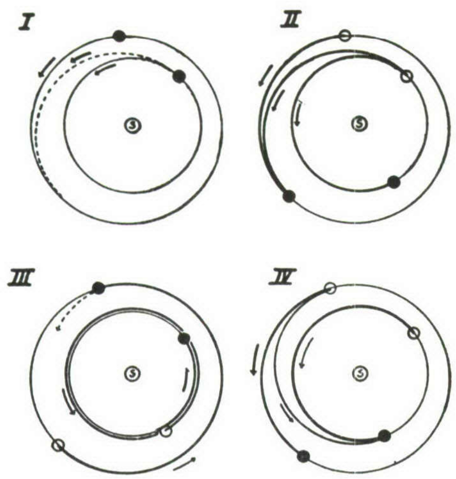

Fig. 1. A trip to Mars and back. (I) Position of planets (black circles) at beginning of trip (broken line shows orbit traveled by spaceship). (II) Position at moment of arrival on Mars (previous position shown by white circles). (III) Position at date of departure from Mars (Mars has completed the whole journey from the white to black circle and the earth has traveled around its whole orbit almost one and one-quarter times). (IV) Position at date of spaceship's arrival on earth. (Courtesy of the Viking Press: Rockets and Space Travel, by Willie Ley).

if the speed of the ship, relative to the center of the moon, is comparatively small. For example, to circle the moon at a distance of 100 km., the space ship must have a tangential velocity of 1.17 km./sec. relative to the moon's gravitational center. Accordingly, the ship's average speed will be between the limits of about 11 km./sec. and 1 km./sec. Its exact velocity will be determined by the characteristics of that orbit which results in the most economical energy consumption. Under these circumstances, the distance to the moon would be covered within a period of about twenty to forty hours. When traveling to the neighboring planets, Venus and Mars, the space ship must leave the earth-moon system. For reasons of fuel economy the ship must, as soon as possible, take a course similar to the orbit of a comet around the sun. The elements of this orbit should be such that the space ship is brought near to the target planet in such a manner that, on arrival, its speed as to direction and magnitude approximately equals that of the planet. Orbits of this kind are, in general, elliptical; their eccentricity is about 0.8 to 0.95. Figure 1 shows some examples of orbits which were calculated by Hohmann about thirty years ago. In the center of the figures we have the sun; the inner circle represents the orbit of the earth, the outer one that of Mars. The black dots on each orbit indicate the position of earth and Mars, respectively, at the moment when the space ship leaves the home planet. Once the gravitational field of the earth has been overcome, the space ship must be accelerated by a small amount. This additional acceleration relative to the sun will enable the ship to travel along the ellipse around the sun to meet Mars at the position II. For the travel back to earth, the energy available will be the determining factor. In case we have to save energy at any cost, we would have to wait more than a year in order to get another equally favorable position of the two planets, suitable for an economic orbit. The orbit which leads back to earth is shown by positions III and IV of Figure 1.

As to the lengths of time required to travel to the neighboring planets along such orbits, we can state the following: The ship will travel at ve-

locities close to the order of the revolutionary velocities of planets around the sun at the distances of Venus, earth, and Mars from the sun. These velocities are: Venus, 35.7 km./sec.; earth, 30.5 km./sec., and Mars 25.5 km./sec. The speed of the space ship, therefore, will be around 30 km./sec. The lengths of the respective sections of the ship's orbit to Venus and Mars are about 100 and 200 million km., respectively. The traveling time computed therefrom amounts to about five and ten weeks, respectively, or, for a round trip, ten and twenty weeks.

These lengths of time become important to the physiologist, when considering a visit to any of the neighboring planets, especially since the periods must be spent in a state entirely free of gravity.

If sufficiently large quantities of fuel energy are available, this traveling time could be reduced considerably by continuous acceleration during the first half, and by corresponding deceleration during the second half, of the journey. This would have the further advantage that, during the whole trip we would always have some acceleration in the direction the ship's propelling force is acting (giving us a quasi-gravity of less than 1 g). With a steady acceleration of 0.1 g, for instance, the trip to Venus and Mars could be carried out in about five to six days. The space ship would in this instance attain a peak velocity of 200 to 250 km./sec. relative to the sun.

After the space ship has left the earth, it will be necessary to employ extremely accurate navigation in order to check constantly whether the ship is traveling along the preassigned orbit. Speaking astronomically, the elements of the ship's orbit must be under constant surveillance. The problem of navigation of a space ship has been discussed frequently in numerous publications. The navigation of a space ship is accomplished by taking planetary bearings relative to the background of the fixed stars. As long as the distance of the ship from earth is small, the earth's diameter, its angular distance from the moon, and their relative projections against the background of fixed stars, will permit navigation of sufficient accuracy. Yet, with the space ship at a point about halfway between earth and Mars, for instance, the accuracy required is very high. In view of the immense distances involved, we will have to deal with two main difficulties:

1. The residual rotation of the space ship. After leaving the terrestrial atmosphere, and after cutting off the driving rocket mechanism, the space ship will rotate about an axis which cannot be determined beforehand. The rotational period will also be unknown beforehand. Even if the rotation of the ship can be controlled by either lateral drives or a three-dimensional gyroscopic device, the space ship will always have slight shifts in rotary balance, since any movements of the occupants will affect the ship's rotatory period and axis. These slight oscillations, due to the unavoidable rotatory shifts, constitute considerable astronautic difficulties, since the accuracy of the sextant is inadequate. Bearings taken by means of transit instruments must be corrected with respect to the rotatory shifts, but, as mentioned

above, a technique for determining the degree and variations of such shifts has yet to be devised. Photographic methods and statistical evaluations of visual observations may solve this problem.

2. The problem of clock corrections. It will be difficult for the crew of the space ship to correct their timepieces with the accuracy necessary for a journey into cosmic space. Astronomical time measurements are impossible because for this purpose the position of the ship within the solar system must be known in advance. Observation of objective astronomical phenomena (eclipses of the earth, its moon and Jupiter's moons) will not help, since for these cosmic distances the finite velocity of light cannot be neglected. As long as time signals can be received from the earth, time corrections can be performed with sufficient accuracy because the diameter of the earth, as measured by the visual angle, or the angular distance between the earth and moon, will permit a satisfactorily accurate computation of respective distances from the earth. Thus we are able to take into account the time interval which elapses between transmission and the reception of the signals.

There is another technique which might possibly be of assistance in accomplishing space navigation. If a powerful light source were available on the space ship, the space ship could be observed by a terrestrial observatory. If the lamp were of 1,000,000 candle-power and had a signal duration of twenty minutes, the space ship could be observed by the most powerful telescopes to a distance of about three times that of the moon. This illustrates the immense power of modern astronomical instruments. Because it takes the ship about a day and a half to travel this distance of about 1,000,000 kilometers, it would be possible to photograph the light of the ship during the twenty minutes of the signal's duration. One observation could be made at the beginning of the night, a second at the end of the night, and a third at the beginning of the next night. Then, the position of the ship at three periods, necessary as a basis for calculation of the orbit of a celestial body, would be available. The elements of the ship's orbit then could be calculated in the calculating division of the observatory, where all facilities for an accurate and fast calculation would be available. The elements of the orbit, plus the necessary corrections could be transmitted to the ship which, at this time, would still be within the reach of modern transmission equipment.

The space ship traveling through space is exposed to radiation of various kinds. The solar radiation hits the ship's outer hull in its original form, i.e, undiminished by the filter effect of the atmosphere surrounding the earth. In this case we must consider the hull of the space ship as quasi-atmosphere, affording a protection similar to that which the terrestrial atmosphere gives to all life on earth. The hull should be able to absorb, reflect, or transform the sun's radiation. Fortunately, in order to anticipate the results, no major difficulties will be encountered; on the contrary, the solar radiation will be of great usefulness for maintaining the comfort level of temperature inside the

ship without any heating devices. The extraterrestrial solar radiation differs from the radiation mixture which hits the earth's surface only in the non-visible ranges of infrared and ultraviolet radiation. Only the ultraviolet radiation, which normally is filtered to a large extent by the terrestrial atmosphere, has a harmful effect. This ultraviolet radiation easily can be either absorbed or reflected by metal, i.e., in our case, by the hull of the space ship. The windows of the space ship must likewise possess an adequate absorptive quality. This is highly important in view of the local solar eruptions which eventually radiate an extremely high rate of ultraviolet radiation. In the range of wave lengths between 1,500 and 2,000 Ångstroms, one can occasionally observe an intensification of the radiation by 10 to 100 times. This corresponds to a radiation increase in the field of eruption on the sun's surface by 1,000 to 10,000 times, since the area of these fields covers about one hundredth of that of the whole sun. The window structures of a space ship must cope with these values. Streams of corpuscles, such as the sun occasionally emits to give rise to the aurora borealis here on earth, are very rare and dispersed. Furthermore, the velocity of these particles is too low (1600 km./sec.) to produce any harmful effect.

As mentioned before, maintenance of a proper temperature level within the ship is of major importance. The laws of radiation, in connection with the knowledge of the respective spectral absorption coefficients of the hull's material, permit a fairly accurate calculation of the equilibrium temperature the ship will attain.

Whereas the various kinds of radiations prevailing in space hardly will be harmful to the passengers of a space ship, there is a hazard which must be anticipated seriously—the possible collisions of the space ship with meteorites. Numerous calculations as to this probability have been made. In view of the greatness of this hazard, we thought it necessary to study this problem in detail.

The space of the planetary system is interspersed with a large number of meteorites which, in relation to the space ship, travel at high speeds. According to their velocities and characteristics of their orbits, the meteorites are classified into two groups:

1. The system of the interstellar small bodies which traverse the spaces of the solar system in chiefly hyperbolic orbits. Their velocities near the earth range above 42 km./sec.

2. The swarms of meteorites pertaining to the solar system. Some of these have been proved to be relics of decomposed former comets. These swarms revolve around the sun in ellipses of varying eccentricity, and their velocities near the earth are less than 42 km./sec. There is a periodical occurrence of meteorite showers during certain periods of the calendar year. These showers occur whenever the earth, during its trip around the sun, intersects the orbit of such a meteorite swarm. The density of meteorites within the swarms pertaining to the solar system is much higher than that of the system of the interstellar small bodies, but fortunately, the solar swarms are composed of much smaller particles, most of them being fine dust-like particles. The average density of

meteorites in space has been determined by various astronomers. Determinations of this kind are difficult, and, for this reason, the figures arrived at by the different astronomers differ considerably. Taking the findings of Schalén, H. N. Russell, C. Hoffmeister, and F. Noelke, the average concentration of meteorites in space lies between the limits:

$$3 \times 10^{-24} \text{ per cm}^3 < N < 9 \times 10^{-22} \text{ per cm}^3$$

N is the number of meteorites. The results differ by the factor 300. Yet, these figures are valuable for a calculation of the probability of a collision. In calculating this probability, certain assumptions as to the size of the ship's cross-section must be made, whereas the speed of the meteorites is fairly well known. The result is as follows: Taking, for instance, the higher figure for the mean density of meteorites in space, a collision of the space ship with a meteorite must be anticipated within the period of about one month. These figures constitute a considerable hazard for the crew of the space ship. The high velocities of meteorites give them the power to puncture even thick steel plates. The collision with a meteorite of several hundred grams —which size, fortunately, is very rare —would, by resulting in instantaneous loss of the cabin air, be catastrophic.

The last part of this discussion will concern the conditions to be anticipated on the moon and on our neighbor planets, Venus and Mars. Compositions of atmospheres and prevailing temperature ranges will be the most important factors.

Starting with the moon, we have to state that it does not have any detectable traces of an atmosphere. All investigations apt to discover a lunar atmosphere have failed to do so. In addition to this, there is theoretical evidence that the moon, if it ever had an atmosphere, would have lost it within a short period of time. The moon's gravitational force—it being about 1/6 of the terrestrial value—cannot prevent the molecules of a gaseous atmosphere from dissipating into space. As a result of the absence of an atmosphere, the solar radiation hits the lunar surface unimpaired by any atmospheric absorption. For the same reason, the lunar surface does not have any mechanism for preventing the heat from being radiated during the night; the result is a pronounced drop in temperature. Taking the lengths of day and night on the moon—two weeks each—into consideration, the temperature of the lunar surface is subjected to strong variations. There are extreme temperatures of +135° C. at noon, and of —170° to —200° C. at night. In the depths of the craters sheltered by shadows from the direct sunlight, one may find places where the radiation of the heated lunar formations produces ground temperatures from 0° to 40° C. for limited periods of time. Yet, even if the difficulties resulting from the temperature hazards could be overcome, leaving the space ship on the moon with an air-conditioned protective suit would be hazardous. The freedom of movement would be limited in such a suit, especially due to the moon's small gravitation. The muscles and the equilibrium co-ordination of man are primarily adapted to the conditions prevailing on earth. Moreover, the sur-

face of the moon presumably is covered with a more or less thick layer of finest dust, which is partly of meteoric origin and partly a product of weathering. Yet, weathering is hardly the right expression in view of the absence of a lunar atmosphere; for millions of years, a strong variation of temperature, with a change of more than 300° C. every two weeks, has been tearing and working at the rocks of the moon's surface, grinding them to dust. The debris has never been blown away by winds or washed away by water, since there is no atmosphere. This layer of dust constitutes a further impediment to walking even if we disregard the prevailing temperatures.

Venus, the inner neighbor of earth in the solar system, is the planet most similar to the earth. It has about the same size and mass as the earth; its gravitational field is 0.84 of the terrestrial value. The surface of Venus, however, is constantly covered by a thick layer of white clouds whose nature still is undisclosed. Weighing the physical similarity, one may expect almost earthlike conditions on Venus, as far as temperature and climate are concerned. Yet, this is not the case, as a number of successful investigations on the Venusian atmosphere, its composition and its temperature, have demonstrated. These investigations were carried out chiefly by Adel at the Lowell Observatory near Flagstaff, Arizona. Adel attempted a chemical analysis of the atmospheric gases of Venus. In the infrared part of the Venusian spectrum, characteristic absorptions were found which were compared to tests carried out in the laboratory. The results of these comparison studies established that the specific absorptions present in the Venusian spectrum are those due to carbon dioxide, which must be present there in considerable amounts. This was concluded from the fact that an absorption less than that observed in the Venusian atmosphere could be produced from a layer of pure CO_2 not less than a mile thick at a pressure of one atmosphere. Water vapor and oxygen have not yet been determined to be present in the Venusian atmosphere. The temperature of the Venus atmosphere—at least for those layers accessible, due to the radiation we can observe—has been determined by spectroscopic means. Again, the spectrum of carbon dioxide, which seems to be the primary atmospheric matter of Venus, was used. A method involving the relative intensity of the different rotational lines of the CO_2-band spectrum revealed temperatures of about 50° C. pertaining to these high atmospheric layers. The large quantities of free carbon dioxide must produce a powerful "greenhouse effect," with the result that the surface temperature of Venus will hardly be less than 150° C.

Mars, the outer neighbor of the earth in the solar system, seems to be, thus far, the only friendly body in the list of planets we can possibly reach. Figure 2 shows photographs taken of Mars at the Lick Observatory near San Jose in California. The two upper pictures are also shown as

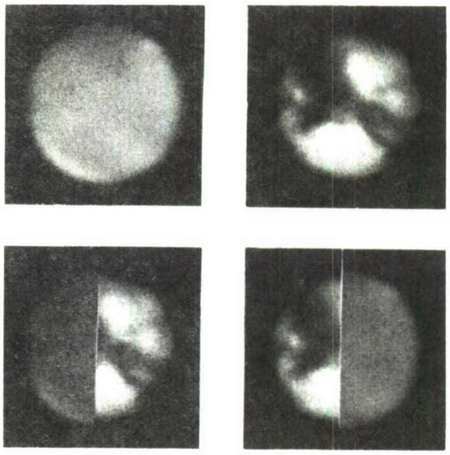

Fig. 2. Photographs of Mars by violet and red light, with halved images for comparison. (Courtesy of N. U. Mayall, University of California).

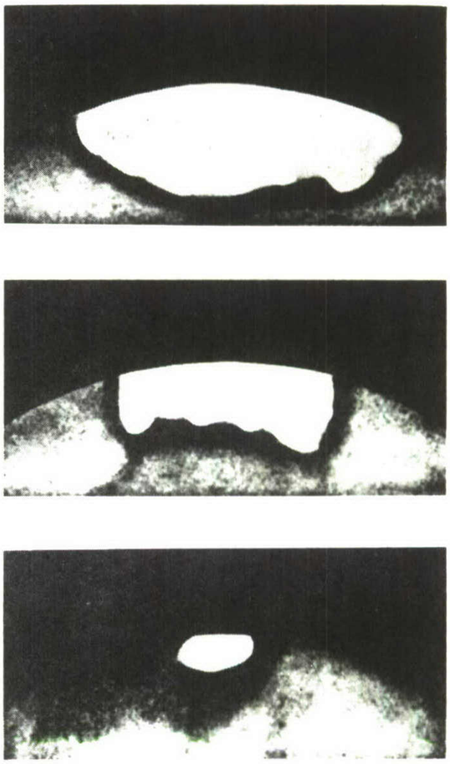

Fig. 3. Diminution of the southern polar cap of Mars, July to September, 1924. *(Above)* July 20, longitude 300°. *(Center)* August 25, longitude 5°. *(Below)* September 5, longitude 230°. (Courtesy of Springer-Verlae: Handbuches der Astrophysik, vol. 4, pp. 376 and 379).

halved images, for comparison of size. The larger one was taken with a violet filter, the smaller one with a red filter. The difference in size is due to the fact that blue rays, characterized by small wave-lengths of light, are scattered and reflected by the Martian atmosphere yielding a picture of Mars that includes parts of its atmosphere. The red rays, characterized by longer wave lengths of light, have the power to penetrate the atmosphere; they are reflected by the solid surface of Mars and yield a picture of the planet itself without the atmosphere. These pictures establish clearly the presence of a transparent atmosphere—more transparent for red light—similar to the characteristics of our own atmosphere. Even more so, another feature, familiar to man here on earth, is demonstrated by Mars, and has been observed for years. Figure 3 shows three pictures of Mars, taken with an interval of about one month between each. The period covers the Martian season of spring for the hemisphere in question. In the first picture, the polar area of Mars is covered by a distinct white cap which, during the period of roughly two months, recedes and almost vanishes. This observation was taken to be a seasonal melting process, though the exact nature of the "snow" remained unknown. Taking the results of former temperature determinations on Mars—0° to —100° C.—the white polar caps could consist either of ice or of solid carbon dioxide. Within the temperature range prevailing on Mars, carbon dioxide could

freeze out of the atmosphere and settle down in the polar region. The increasing temperature during the spring season would cause the solid carbon dioxide to vaporize. A decision as to whether the polar caps consist of carbon dioxide or of ice was recently made possible. Both substances can be differentiated by their respective reflection coefficient in the infrared region of the Martian spectrum. By means of a special PbS photo-electric cell, this difference could be observed in the case of the Martian polar caps. It was determined that the polar caps consist of ice, or, rather, a thin layer of frost, since they melt away rather fast. We, therefore, can conclude that water vapor is present in the Martian atmosphere, possibly accounting also for thin clouds which have been observed on Mars occasionally. Search for the presence of oxygen has been unsuccessful to date; a definite decision as to the presence of oxygen on Mars can hardly be expected, since all observations to this effect necessarily must be made through our own atmosphere where oxygen is abundant. However, possible limits of the abundance of Martian oxygen can be established. Thus, we know that we have to expect less than 1/300 of the terrestrial amount of oxygen, if any. The Martian atmosphere probably is built up chiefly of nitrogen and the heavier rare gases, with traces of carbon dioxide, water vapor and possibly oxygen. During the latest opposition of Mars, the presence of lower forms of life was indicated as probable on Mars. By comparing the spectrum of the greenish spots on Mars, appearing occasionally during the Martian spring and summer season, with the spectrum of terrestrial plants here on earth, it was concluded that certain species of mosses and lichen-like plants exist on Mars.

Thus, a survey of the neighbor worlds of our earth reveals that Mars seems to be the sole celestial body in our neighborhood on which man can set foot without encountering too great difficulties.

Dr. Hubertus Strughold

Whereas the physical and astronomic study of space flight is based on the solid foundation of natural sciences, the physiological study seems to add new problems to the great mystery of life. Yet, modern physiology can make certain predictions that are well based on scientific facts as to physiological possibilities, limits, and support by physiological means. This is possible due to the scientific progress made and experiences undergone in aviation medicine and submarine medicine, especially during the last fifteen years.

The physiological problems of space flight arise on the whole from the following fact: Man on earth is exposed and adapted to certain terrestrial and extraterrestrial factors and conditions. The terrestrial factors are: the gravity of the earth; the tensions of the atmospheric gases, which incidentally depend also on gravity; the rotation of the earth; the revolution of the earth, et cetera. The extraterrestrial factors consist mainly of the solar rays, which supply the atmosphere with light and heat energy and determine its water balance. The combined actions

of terrestrial and extraterrestrial forces constitute certain physical conditions to which man, animal, and plant are exposed and adapted.

If man is lifted from earth in a space ship, a shift occurs in the balance between terrestrial and extraterrestrial, or sidereal, energies and conditions to which he is accustomed. He moves away from the terrestrial environment, and, after leaving the protecting atmosphere, becomes exposed to a greater extent to solar and cosmic energies and strange conditions which exist on other celestial bodies. The terrestrial milieu is replaced by the interplanetary one, which is free of gravity and oxygen but rich in radiated energy and in meteorites. Or, it is possibly replaced by the milieu of the moon or of planets.

The problems which arise then in space medicine are briefly the following:

1. Tolerance of the conditions resulting from the absence of terrestrial factors and from the increase in radiated solar energies.

2. Artificial maintenance of quasi-terrestrial conditions in the space ship and protection from solar energies and meteorites.

3. Prospects of life and artificial means of sustaining life on other celestial bodies.

These three problems can be classified under the physiological milieu problems of space travel.

Another vast complex of physiological problems arises from the technical process of the travel. It is, therefore, inherently connected with the navigation of the space ship. Speed of the space ship and velocity of the mental processes involved in its control, latent time of perception and recognition, reaction time during take-off and landing, the so-called "dead distances" which are covered by the reaction time, time sense, and acceleration—these are the principal problems which are included in the complex of the physiological navigation problems of space flight. Gravity and acceleration represent the connecting link between these two large complexes.

A third complex of problems has more of a psychological nature, involving, as it does, the problems of psychic aptitude, fatigue, living in a confined room for a rather long time, et cetera. This complex may be designated as the psychological problems of space flight, which naturally are closely connected with the milieu problem and the navigation problem.

Due to the shortage of time, I am going to discuss only a few problems, particularly those that are related to my special field of work in physiology.

A comfortable physiological milieu requires adequate oxygen supply. In this connection I would like to discuss only the storage of a sufficient amount of oxygen in the space ship. We can assume that the oxygen consumption of the astronaut is very low. This would tend to minimize the whole problem, since under gravity-free conditions no work has to be performed to overcome gravity; we think that the metabolic rate would not significantly exceed that of basal metabolism. Unless exercise is indicated in the space ship to avoid muscle atrophy, the maximum amount of oxygen required might be around 500 liters per day per

person. The oxygen problem can be further minimized by utilizing the upper limit of physiological tolerance of increased oxygen pressure. As we know, the minimum oxygen pressure required in the air is about 100 mm. of Hg. At a pressure lower than 100 mm., the individual succumbs to altitude sickness. Furthermore, through the experiments of Behnke, Clamann, and others, accomplished during the last ten years, we know that man can tolerate increased oxygen pressure as high as 425 mm. of Hg for a prolonged period of time without suffering any injuries. At pressures above this level, symptoms of oxygen poisoning will appear after several days' exposure.

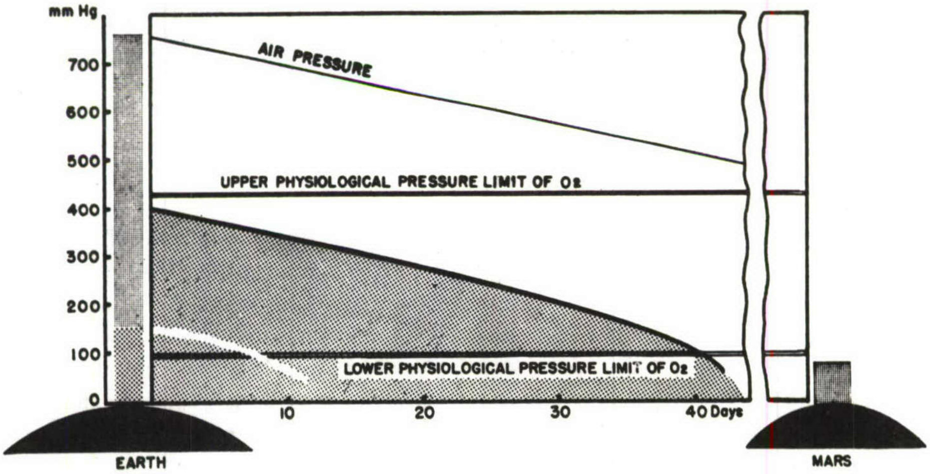

Fig. 4. Utilization of physiological tolerance of oxygen pressure on a trip to Mars.

As economy has to be practiced in regard to oxygen consumption in the space ship, it seems advisable to utilize this range of physiological tolerance of oxygen pressure. The advantages involved in this method are shown in Figure 4. The left column shows oxygen pressure and air pressure on the earth; the right side, the air pressure on Mars.* If 40 cubic meters of air were available to a person in a space ship, then the normal oxygen pressure of 160 mm. would be reduced by respiration at a rate similar to that shown by the lower curve. Within five to six days the lower physiological limit of oxygen pressure would be attained. However, if the pressure of oxygen were increased to levels indicated by the shaded area, for example, up to 400 mm., that is, close to the upper physiological oxygen limit, the lower physiological limit of oxygen pressure would be reached only after several weeks. Consequently, if we utilize a higher pressure of oxygen, we achieve considerable economic advantage. It is obvious that this method is also of great interest with regard to prolonged flights in the stratosphere and ionosphere. The only disadvantage would

*This value for the pressure is only tentative.

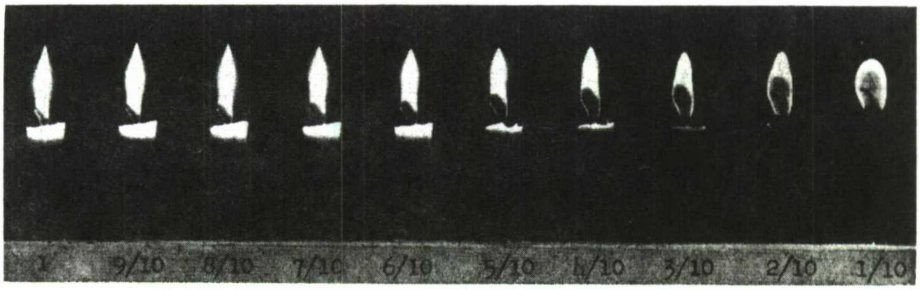

Fig. 5. Flames of a candle burning at different degrees of decreased atmospheric pressure. On the left is one atmosphere of pressure. The atmospheric pressure falls off to the right in the decrements of 1/10 so that the last candle is seen burning at 1/10 of an atmosphere.

be an increased danger of fire. A further advantage, however, is the fact that, due to the elimination of carbon dioxide by chemical agents or by freezing, the air pressure in the space ship is very gradually adapted to the air pressure of Mars, as it is shown in the upper curve. If we apply this method, all the oxygen that is carried in cylinders is reserved for use on the respective celestial body or possibly on the return trip to earth.

The planetary atmospheres have always been of special interest in regard to oxygen and prospects of life. (See "Life on Other Worlds" by H. Spencer, and "Atmospheres of the Earth and Planets," edited by G. P. Kuiper.)

If we study the planetary atmospheres from the physiological aspects, we must classify them with regard to the quantity and quality of the gases and as to the question of whether they are relatively or absolutely nonphysiological. Apart from temperatures, the atmospheres of Jupiter and Venus are absolutely nonphysiological with regard to their quality; the former contains methane and ammonia gases; the latter abounds in carbon dioxide, according to spectroscopic studies made at Mount Wilson and Lowell observatories. The atmosphere of Mars must be classified as qualitatively physiological but quantitatively nonphysiological. To alight on Mars, it might not be absolutely necessary to wear a pressure suit; the oxygen mask perhaps would be sufficient if the air pressure is above 150 mm. Hg. On Venus and Jupiter, man would have to be tightly sealed in a space suit against the penetration of noxious gases. As for the moon, it is impossible for man to set foot there without wearing a pressure suit, since this celestial body is not able to retain any atmosphere due to insufficient gravity.

A vital factor in living on our earth is the production of energy by oxidation through fire. Origin and maintenance of fire require a certain minimum pressure of oxygen. Figure 5 shows a series of pictures which demonstrates flames at various atmospheric pressures, reduced in each case by one-tenth of an atmosphere. Between one-tenth and one-fifteenth of an atmosphere—that means at an oxygen pressure of about 15 mm.—the candle light is extinguished. The oxygen pressure on Mars, for example, is probably not that high. The astronauts

therefore, may find themselves unable to light a fire on Mars. If the atmosphere of Mars were to contain about 20 per cent oxygen, the picture of the flame would be approximately similar to that obtained on the earth at a height of 50,000 feet, and it would therefore, correspond to the flame shown in the last exposure in Figure 5. On Mars, a flame burning in pure oxygen would be weak and dim, but very extensive—as in Figure 6—corresponding to the low atmospheric pressure which is in part due to the low gravitation of Mars. The flame in this picture is burning in a low pressure chamber in pure oxygen. The pressure corresponds to that existing at an altitude of 15,000 meters (45.-000 feet) in pure oxygen, and that produces a flame that would be similar to one made on Mars in pure oxygen.

Dr. Haber discussed the probability of a collision of a space ship and a meteorite. What would be the physiological effect in case such a collision would actually occur? If a space ship were hit by a meteorite the size of a pea, the effect would be similar to that following the leakage of a pressure cabin aircraft in the stratosphere, although more violent. Within a fraction of a second the conditions of a "hard" vacuum would be attained. In addition to the effect of a superacute anoxia, the result would be a superacute gas edema of the tissues and subsequent destruction of the tissues. The skin, for instance, would form large blisters filled with oxygen, carbon dioxide, nitrogen, et cetera. One can observe such manifestations in rabbits that are exposed to explosive decompression up to 60,000 feet in low pressure chamber. In analogy to the term "horror e vacuo" which was coined in the Middle Ages when the investigations on air pressure were

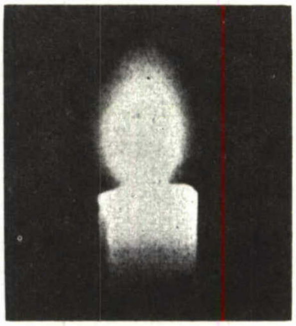

Fig. 6. Flame of a candle in a low pressure chamber at an air pressure corresponding to a height of 45,000 feet but in pure oxygen.

started, we might designate such effects as "gaseous edema e vacuo" or "epidermolysis e vacuo." These manifestations are, of course, only a violent form of aeroembolism. We would encounter the "horror e vacuo" also upon setting foot on the moon without an adequate pressure suit.

I have mentioned gravitation repeatedly. Generally speaking, gravitation is a most important milieu factor. In daily life we do not become aware of its importance, yet, even the plants show the effect of gravity in the form of geotropism. Whereas, aviation presents the problems only of multiplied gravitation, astronavigation has to deal with multiplied and divided gravitation or multiplied and divided g (H. Haber and O. Gauer, W. Ley).

The range of multiplied g comes into play upon take-off and landing, as you have already heard. Because of the shortage of time, I would like to mention only that the multiplied g

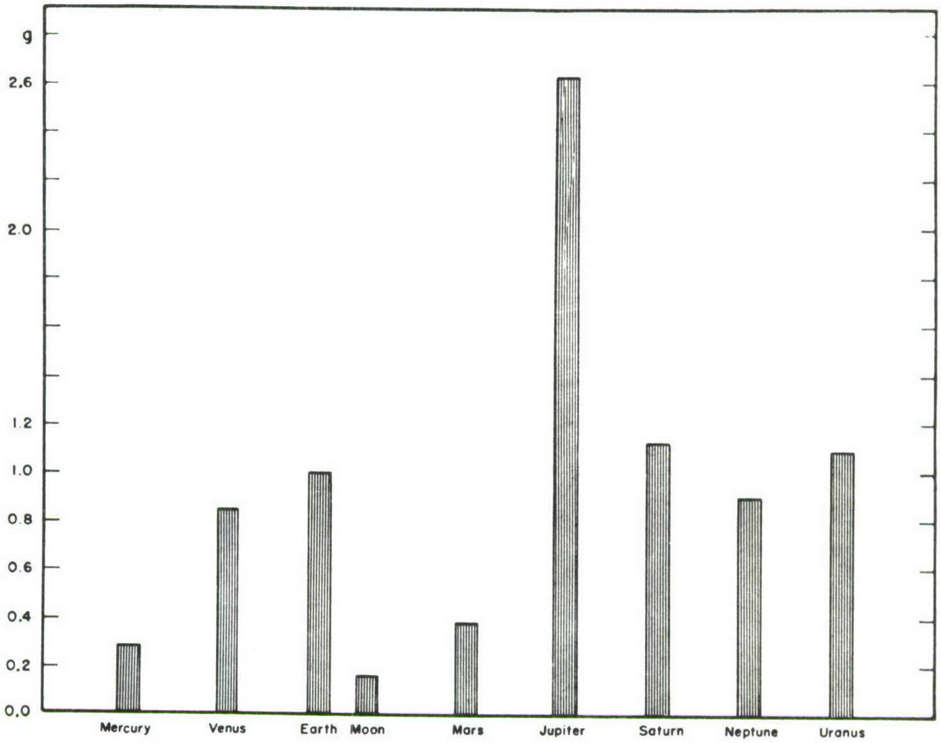

Fig. 7. Gravity expressed in g on the surface of the various planets and the moon.

does not present great physiological problems if proper position of the crew is presupposed. This has been proven by experiments carried out on large centrifuges by Armstrong, Heim, Bergeret, Wood, Gauer, Gougerot, and others.

The range of divided g or of subnormal gravitation, as we might call it from the physiological point of view, is the "terra incognita" of space flight physiology. In the interstellar space gravitation is zero because the space ship is in a state of ideal equilibrium between gravitational and centrifugal force.

Figure 7 gives an over-all picture of gravitation on the surface of the various planets. On Mars, there is 37 per cent of the terrestrial gravity, on the moon 17 per cent.

The physiological problem of subnormal gravitation involves two basic questions:

1. What are the effects of a constant reduced level, or the absence, of gravity?

2. What are the physiological effects of a decrease and increase in gravity in the subnormal range upon leaving and returning to the earth?

Any physiologist will hesitate to make definite predictions here. But let us try to draw, in small sketches, the situation which we must face in the gravity-free space. In a gravity-free state, our weight decreases to

nothing. A feather and a piece of iron have the same weight, or rather both have no weight. If we would move our arm, we would not feel its weight. But the power of our muscles remains the same. One could perhaps compare the work of the muscles in gravity-free space with the light work of the eye muscles here on earth, which do not have to work against gravity but only against friction and tensions. Lifting, for instance, a safe in the space ship requires no more strain than moving the eyes. This strange discrepancy between the muscle energy available and the muscle energy required in gravity-free space might bring some difficulties to our *sensory motor system.*

Normally, the movements of our limbs are controlled by a threefold sensory system, of which the muscle sense and the pressure sense of the skin are best known. But experiments performed about twenty years ago indicate that even when the pressure sense nerves of the skin, for instance of the finger, are anesthetized and the muscle sense is eliminated by a special experimental technique at the same time, we are still able to make very precise movements. The so-called Vater-Pacini corpuscles scattered throughout the tissue can be considered as the receptors for this third component of the control mechanism for the movements of the limbs, according to M. V. Frey. Because tension of the tissue, and not gravity, represents an adequate stimulus for this little-known sense organ, it might have an increased significance in the gravity-free space. For it would be conceivable that this component could, through adaptation, to a certain degree compensate in gravity-free space for the elimination of both the others, which must be considered as gravireceptors.

I am a little optimistic, therefore, as to the sensory motor system of the muscles of our limbs in gravity-free space and as to the sensory control of the movements of our entire body, if a modified basal tonus of the muscles, which depends on the vestibular apparatus, does not spoil the picture.

The movement of the entire body will involve floating in the air of the space ship, and the orientation for movement in the space ship will have to be accomplished optically, whereas on the earth it is done optically, by means of the eyes, and gravireceptorially, by means of the vestibular apparatus muscle sense and the pressure sense of the skin. We do not know whether men can adjust to a purely optical orientation in space. Fish can be trained to an optical orientation in space. Only recently it was found by V. Holst that, when the top of an aquarium standing in a dark room is covered with a black plate and the light penetrates through the glass bottom, some fish will always swim upside down, will look for fresh air at the bottom, and will swim to the dark surface of the water when they want to rest.

With reference to respiration and circulation, the absence of gravity probably involves less difficult problems. The heart muscle, maintaining its power, has less work to perform since the weight of the blood is nil. It is significant whether or not the heart can adapt itself to this situation. And,

if it can adapt itself to the gravity-free space, will it be able to accept the additional stress when gravity returns? Here, at the return to earth, the weak point for circulation seems to arise. We have no reasons to assume that the respiration apparatus will be impaired by the absence of gravity. However, one difficulty, not due to the respiratory apparatus itself, but due to the ambient air, should be mentioned here. No thermal convection exists in the air within the space ship when gravity is absent; hence, the expired air will remain in front of the nose of the astronaut. This means that some type of ventilation must be provided for the space ship's air to prevent the formation of localized bodies of air containing little oxygen and much carbon dioxide.

To conclude the question of subnormal gravitation, I should like to mention the importance of the relationship between basic excitation and additional excitation of the gravireceptors if gravitation is changed. This concept, which is based on Weber's law and which was brought up for discussion for the first time by O. Gauer, can be considered as a basic foundation for the explanation of the disturbances to be anticipated in both the autonomic and the somatic nervous system.

This, in short, sketches the picture of gravity-free space with only some of its physiological problems. We can only guess the facts here; experiments must give the final answer. In case the gravity-free state involves too many physiological difficulties, the physiologist would have to demand a continuous slight acceleration of the space ship to attain a certain amount of quasi-gravity.

Finally, I would like to broach a problem that belongs to the physiological complex of navigation. Of great interest in this respect, for instance, is the comparison between the speed of the space ship and the velocity of the nervous processes involved in its control. This is a space-time-brain problem.

About twenty years ago, when the speed of aircraft had exceeded the velocity of nerve conduction, the reaction time of man was for the first time correlated with flying speed. The distance covered by the reaction time, during which a change in course is impossible for physiological reasons, was called "dead space" or "dead distance." This concept requires further elaboration in supersonic speed. The simple reaction time is 150 to 200 milliseconds. The sensory part of it, the so-called latent time of perception, ranges between 35 and 70 milliseconds. This latency of perception conditions a shift in time or anisochronia between physical reality and perception. The impressions which are produced in our mind lag behind the actual events by one-twentieth to one-tenth of a second. This lag is not noticeable in ordinary life at high speed. This physiological lag, however, becomes evident, with regard to space, as a nonperceptive interval. This is the distance covered during the latent time of perception at the various speeds. At a speed of 1 km. per second the nonperceptive interval would cover approximately 50 to 100 meters, the simple reaction time would cover a physiological "dead distance" of 200 m.

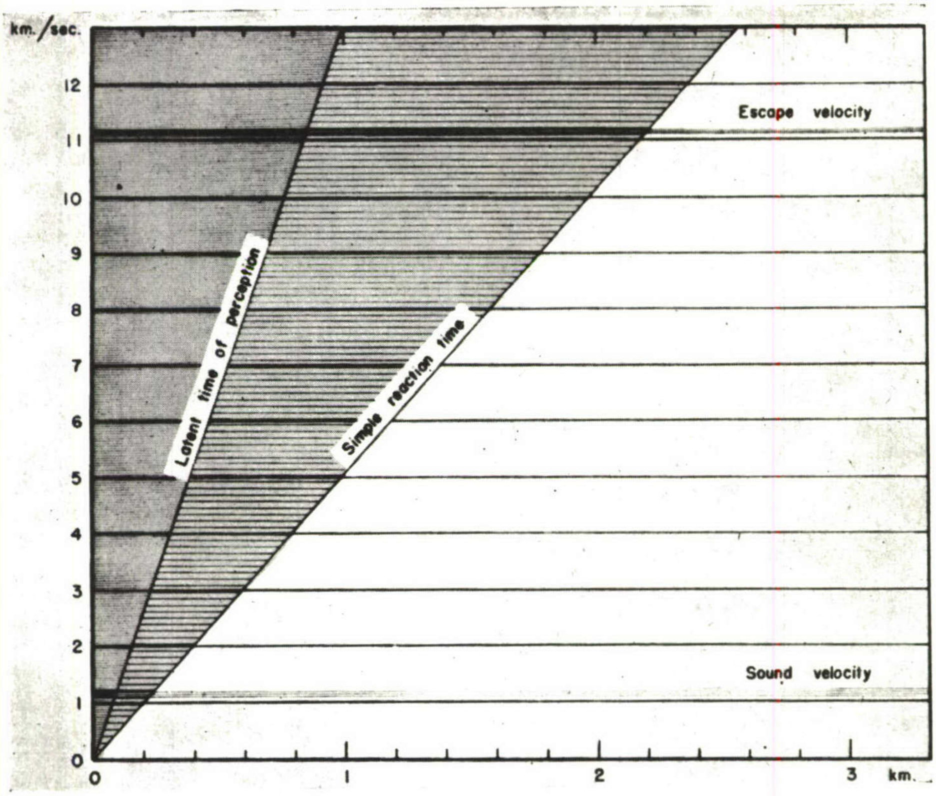

Fig. 8. The distances covered by the latent time of perception and simple reaction time at various speeds. Abscissa: distances (expressed in km.). Ordinate: speed (expressed in km./sec.).

(Fig. 8). With the reactions of higher order, such as recognition reaction time, et cetera, which may last as long as one or two seconds, we have to consider a "dead distance" of up to 1 kilometer and more. If, in addition, we consider the physically dead distance, which results from the lag of the controls of the space ships, we obtain a total dead distance of many kilometers. Over this distance a change in course is impossible because of both physiological and physical inertia. Upon landing or circling around the moon, for example, the existence of nonperceptive and nonreactive intervals must be taken into account.

I would like to conclude this discussion with this brief remark. One might perhaps say that space flight physiology belongs to the realm of imagination. However, we should always be aware of the fact that, in numerous instances, the imagination of yesterday is the reality of tomorrow. And even if a round trip to the moon should never be realized, a meticulous study of the problems arising in this field will reflexly aid in the investigations of the terrestial conditions on our home planet. We might add better understanding, for instance, of our sensory motor system by visualizing its function in the absence of gravity. In

any case the occupation with the subject of space medicine will give impetus to science.

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THE HUMAN BODY IN SPACE

by

Heinz Haber

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

The Human Body In Space

Scientists and engineers have long considered the problems of flight to other planets. As the reality of space travel slowly draws closer, they particularly weigh its effects on man's earth-conditioned frame

by Heinz Haber

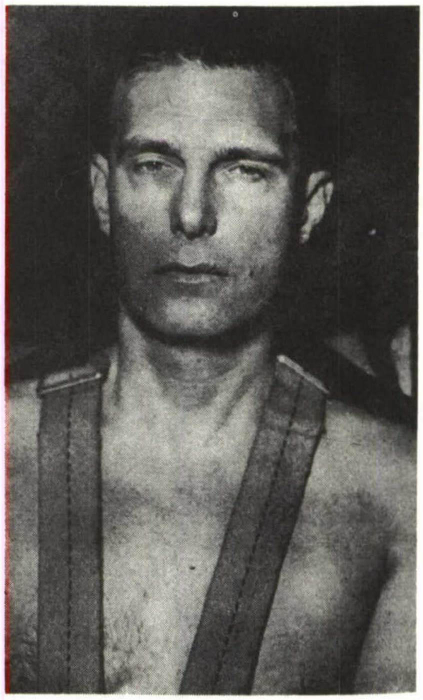
THE GENERAL exploration of our planet has practically come to an end. By means of the airplane civilized man has filled in virtually all the blank spaces on the world's map, and today comfortable airliners fly regularly scheduled flights over wildernesses where courageous explorers perished of hunger, thirst, cold or exhaustion only a few decades ago.

From his conquered home-planet man has begun to look expectantly toward new worlds in the heavens. The Moon and the neighboring planets, Venus and Mars, irresistibly challenge his fancy with the same spell that the seven seas once cast over their explorers. Like the pioneers who first ventured to sea in sailing ships, we are preparing to launch our first frail craft in the vast ocean of space. Already unmanned rockets have risen hundreds of miles from the Earth, and they are going higher and faster every year. It is certain that in the not-too-distant future manned rockets will approach the limits of the terrestrial atmosphere. The next step then will be the launching of a rocket that will permanently circle the Earth outside the atmosphere—an artificial satellite. From this base the Moon will be an island just offshore; Venus and Mars will be nearby continents beckoning to a Columbus.

There is not much point in making predictions as to the timetable of the conquest of space. That will be determined largely by the rate of expenditure of means, manpower and effort. The expenditure required will of course be very high. Space flight is an undertaking which only a large, wealthy nation may dare to tackle. Success will depend on research and development in many fields: thermodynamics, the chemistry of combustion, metallurgy, electronics, aerodynamics, mechanical engineering, astronomy, meteorology, geophysics and so on.

We shall here confine ourselves to a problem that has so far received little scientific attention: namely, the human factor. How will the human explorer fare in his spaceship? What measures must be taken to enable men to survive in the alien environment of the void beyond our atmosphere? These questions open up a new field of science: what may be called space medicine. Space medicine will be an extension of aviation medicine, which developed with the airplane and has now become a large branch of study. In the case of space medicine we shall not be permitted, as in aviation medicine, to explore the problems as they arise. If the enterprise of space flight is to have any chance of success, we must solve the biological problems as completely as possible before we take off into space, in fact, even before our spaceship is designed.

FIRST of all we must reckon with the effects of rapid acceleration. The rocket engine, the only type of motor that could operate in the vacuum of space, works most efficiently at high rates of acceleration. Hence if the spaceship's fuel load is to be kept within reasonable bounds, it will have to accelerate as rapidly as possible. The space traveler will gain in weight in proportion to the acceleration of the ship during takeoff. The ship must accelerate in several stages, each lasting between one and two minutes. Toward the end of each period the crew would have to take an increase in body weight of about sixfold to tenfold. This grazes the limit of human tolerance, as measured in the centrifugal machines now used to test the effects of accelera-



ACCELERATION exerts powerful effects on the human body. It is studied by space medicine because rockets operate most efficiently at

tion on fliers. We can therefore conclude that young persons endowed with healthy circulation will be able to master the hazard of acceleration in a spaceship's ascent, provided they lie in a prone position.

After the ship has accumulated a sufficiently high velocity and left the Earth's atmosphere, its rocket engines will be shut off entirely. It will then travel on its momentum, without resistance in the emptiness of space. Now a new phenomenon will set in: the ship's occupants will lose all weight. There is a common misconception that the effect of gravity will be felt until the ship gets beyond the Earth's effective gravitational field. This is not true. The forces of inertia acting on the ship will balance the pull of the Earth, just as the centrifugal forces acting on the Moon keep it serenely on its course without danger of its being pulled to the Earth. As soon as the rocket motors stop, the spaceship and everything in it—the passengers, even the very air they breathe—will be devoid of weight.

In most discussions of space travel the consequences for the passengers of this weightlessness have been taken lightly. In fact weightlessness evokes a pleasant picture—to float freely in space under no stress at all seems a comfortable and even profitable arrangement. But it will not be as carefree as it seems. Most probably nature will make us pay for the free ride.

There is no experience on the Earth that can tell us what it will be like. True, the first instant of free fall in a dive from a diving board approximates the gravity-free state associated with ideal free fall, but it lasts only a moment. To imagine what complete weightlessness will mean we must resort to our general knowledge of physical and physiological principles rather than to experience.

IT appears that we need not anticipate any serious difficulties in the functions of blood circulation and breathing. These are powered chiefly by the muscles of the heart and the elastic forces of the blood vessels, the midriff and the chest, which are independent of gravity. The weight of the blood plays some part in circulation, but not an indispensable part.

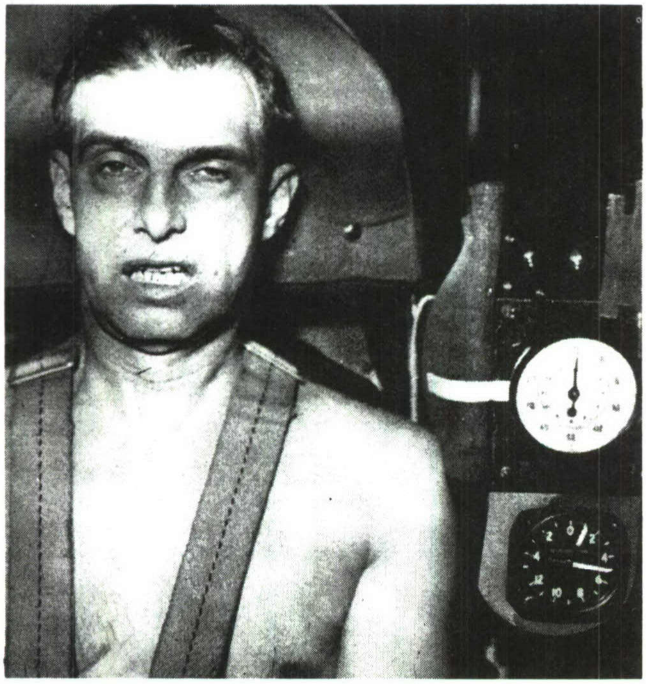
It is in the nervous system of man, his sense organs and his mind, that we can expect trouble when the body becomes weightless. The body possesses an intricate system of receptors which provide detailed information of all kinds of mechanical stimulation. Among these mechano-receptors are the receptor organs for rotatory and translatory motion in the inner ear, the receptors responsible for the pressure sense of the skin, the muscle spindles imbedded in all muscles that fix and move bodily masses, and the so-called Pacinian or Vater's corpuscles found throughout the connective tissues, especially near the muscles.

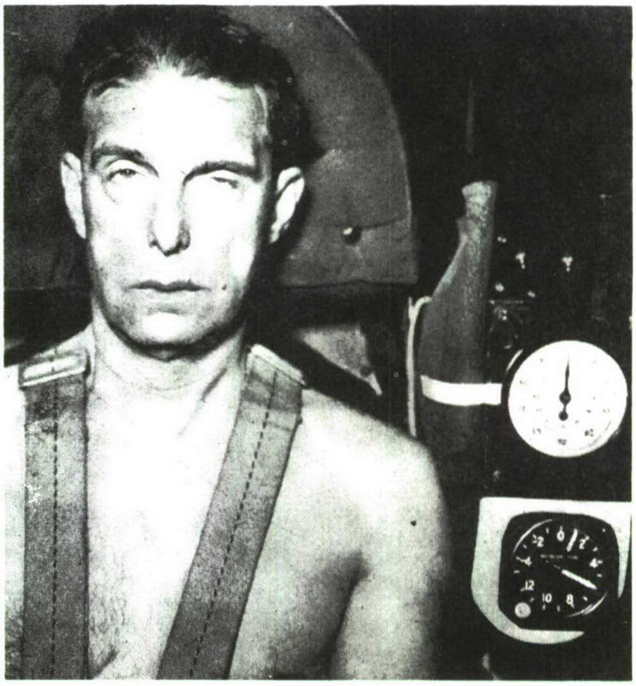
The last three receptors are chiefly responsible for man's special posture sense. They form a functional union controlling the perception of position and of active and passive movements of the body. Their stimulation is closely linked to a complicated reflex mechanism which serves to maintain equilibrium and to regulate bodily movements.

Now the lack of gravity would affect the posture sense and the power sense to a very different extent. The functioning of the posture sense would hardly be affected at all, since the tension of the connective tissue that provides the stimulation for its receptors is independent of weight or the lack of it. The end organs of this sense, in other words, give notice of the various positions of the limbs independently of outside forces. In contrast, the power sense, involving the muscles, is substantially affected by gravity. To move an arm, for example, the muscles normally must overcome not only the inertia of the arm but also its weight.

It is easy to see, therefore, that the lack of gravity would seriously disturb the harmony of the various sense mechanisms that control bodily movements. In a state of weightlessness the muscles would need to overcome only the body's inertia, but they would behave as if they also had to reckon with its weight. Hence the slightest effort by the space traveler to move his body would jerk him across the cabin. Man in space would therefore have to adapt his power sense to an entirely different pattern of forces.

Then there is the question of the body's orientation with respect to ob-





high acceleration. The effects of acceleration are recreated in these photographs, which show a human subject being whirled in the great centrifuge of the Air Force Air Materiel Command at the Wright-Patterson Air Force Base. The increase of gravity is given on the dial at the lower right-hand corner of each photograph. In the first photograph the subject takes 2 g. In the second he takes 5 g. In the third he takes 6 g, "blacks out."

jects around it. Two different mechanisms control this orientation: the eyes establish the position of the body relative to other objects; the mechano-receptors, stimulated by the weight of the body and its parts, register the direction of gravity. Ordinarily both of these perceptions match. But in the state of weightlessness they will be out of kilter; the eyes and the mechano-receptors will register entirely different pictures of the body's situation.

It is possible, however, that space travelers can be trained to orient themselves solely by means of the eyes. Experience in training aviators for blind flying indicates that man is capable of suppressing false information from his system of mechano-receptors. A pilot who flies through a solid overcast relies wholly on visual cues from his instruments. Through these alone he establishes orientation of his position and that of his plane in space. His mechano-receptors may give him the impression that he is flying level when he is actually ascending or descending; only his instruments can give him the correct picture.

In a weightless body at rest the mechano-receptors are inactive. They will be stimulated, however, by every movement of the body. During these movements the forces of inertia will lend weight to the body in proportion to the acceleration applied. While the mechano-receptors are thus placed under stimulations that vary greatly as to direction and size, the eyes will register the situation very differently. Here again is another factor causing dissociation of the various qualities of perception and sensation.

This dissociation may well produce a spatial counterpart of airsickness. Recent investigations have revealed that a disharmony of the perception and sensation complex can induce certain forms of seasickness. We must therefore reckon with the possibility that weightlessness will cause a kind of "space-sickness" that could incapacitate the crew of a spaceship.

CONSIDER still another factor. It is well known that the sensitivity of sense organs increases greatly as the strength of stimulation is reduced. For example, the eye, which barely registers the light from a flashlight in bright sunlight, is dazzled by the very same flashlight in a dark place. Prolonged darkness so enhances the sensitivity of the eye that the faintest glow becomes visible and an ordinary light, suddenly turned on, emits a painful glare.

Presumably the lack of gravity in a spaceship similarly will heighten the sensitivity of the gravity sense. The gravity-sense organs will react vehemently to the smallest forces acting on the body. Moreover, the slightest movement by the spaceship passenger is likely to make him a victim of curious deceptions. If he merely stretches his body or turns his head, he may be overwhelmed by the sensation that he is being lifted and jerked back and forth or that he is suddenly spinning around. A man liberated from the shackles of gravity would most probably be in a constant state of physiological and psychological tension.

Aside from his physiological difficulties, the weightless man would have to contend with the surrounding objects, which, being devoid of weight themselves, would play remarkably mean tricks. Loose objects, large and small, would float around aimlessly inside the cabin, and the passengers would have to keep a wary eye on them. This unremitting struggle with the weightless objects would add to the psychological stress on the travelers.

Possibly the perils of weightlessness might be avoided by some artificial substitute for gravity. For instance, the travelers' cabin might be rotated or might be suspended from the rocket at the end of a long cable and be swung around continuously. Centrifugal force would then restore the passengers' weight. Unfortunately, however, the so-called Coriolis forces which affect all bodies moving within a rotating system would introduce a new discomfort. A passenger would be all right so long as he was at rest, but whenever he moved a limb the Coriolis forces would pull it sideways; every voluntary movement would give the traveler the peculiar illusion that he was being moved haphazardly.

It has been suggested that the crew of a spaceship might be anchored to the floor by equipping them with iron shoes and magnetizing the floor. This, however, would probably add to the travelers' confusion, for while their shoes would be attracted to the floor, their nonmagnetic bodies would not. Moreover, the electronics engineer of the ship doubtless would object strongly to the havoc wreaked upon his intricate instruments by the floor's magnetic fields.

WHAT about air for breathing and the control of the cabin temperature? Our experience with submarines and sealed cabins in high-altitude airplanes indicates that the problem of supplying oxygen and ventilating the cabin in a spaceship will present no particular difficulties. But keeping the cabin at the proper temperature for its human passengers will raise entirely new problems.

Once the spaceship has left the Earth's atmosphere and the Earth's heat, its temperature will depend primarily on how much solar radiation it absorbs. The main problem will be to keep the ship cool enough. Its shell must be made of a material that will reflect most of the solar radiation. Only the very best reflectors, such as magnesium oxide, offer any possibility of keeping the ship at a reasonable temperature. The ship must also radiate away the heat it absorbs and the heat produced by its passengers and the many electrical and mechanical devices inside the craft. The difficulty is that at normal room temperature objects get rid of heat at an extremely low rate.

Another serious problem will be the protection of the passengers against ultraviolet radiation, which the sun sometimes emits in great extra bursts. The Earth's atmosphere filters out nearly all of this radiation, but in space the ultraviolet eruptions would hit the ship unimpeded. The harmful effects on the body of excessive ultraviolet radiation are well known. The metal walls of the spaceship would ward off ultraviolet rays, but no transparent material can remain transparent under massive ultraviolet irradiation. Hence much of the time the ship's windows will have to be kept covered; they can be unhooded only occasionally for necessary observations.

How great would be the hazard from cosmic rays? This is still a controversial question. The recent discovery of heavy primary particles in the upper atmosphere—particles ranging up to an atomic weight of 40 or more—suggests that the cosmic rays might indeed be dangerous. These particles crash into the atmosphere with energies millions or billions of times greater than those that can be produced in a laboratory. To keep them out entirely the spaceship would have to be encased in steel armor plate at least two inches thick. Such a weight of steel is entirely out of the question for a spaceship. Consequently we must resign ourselves to the fact that the passengers would inevitably be exposed to a certain amount of cosmic radiation, not only heavy primaries but powerful secondary particles and gamma rays.

In view of this bleak picture one might better resolve to call off space flight and stay behind the stout shield of our planet's atmosphere. The danger is not, however, as great as may appear. Although the cosmic particles carry tremendous energies, their density in space is inconceivably low. It has been estimated that at an altitude of 80,000 feet an individual would absorb radiation at a rate only about 25 times greater than the permissible weekly dose. At this rate short trips into space would most probably be safe. Radiation effects might, however, become serious over the weeks and months of an extended trip.

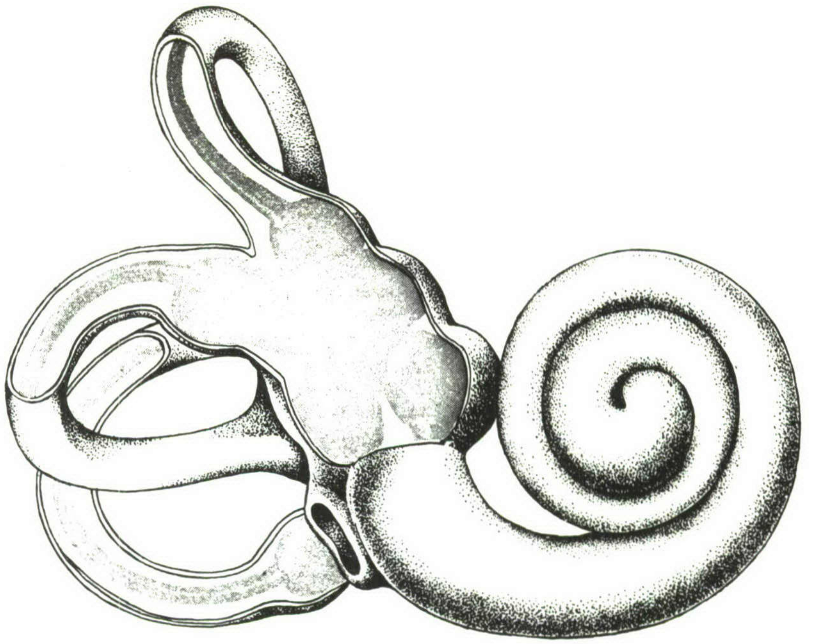
THE spaceship would also run the gantlet of those other stray bullets in space: meteors. Even a meteor the

size of a pinhead, flying at the meteoric speed of 20 to 60 miles per second, could easily puncture the steel hull of the ship. The vaporizing heat from the impact of a meteor would cause a minor explosion at the site of the hit. As it blasted a hole in the wall, the only shield between the passengers and the emptiness of space, the passengers would be subjected to a more or less explosive decompression, depending on the size of the hole. They would have something like 15 to 30 seconds to act before losing consciousness. The damage from a small meteor might possibly be checked by plugging the hole or by a system of air locks. But a hit by a meteor weighing an ounce or more would abruptly end the voyage. Meteors as large as this are believed to be so rare in space, however, that a spacecraft of the size now postulated might cruise for hundreds of years without meeting such a catastrophe. It is estimated that the ship would encounter tinier but still dangerous meteors about once a month.

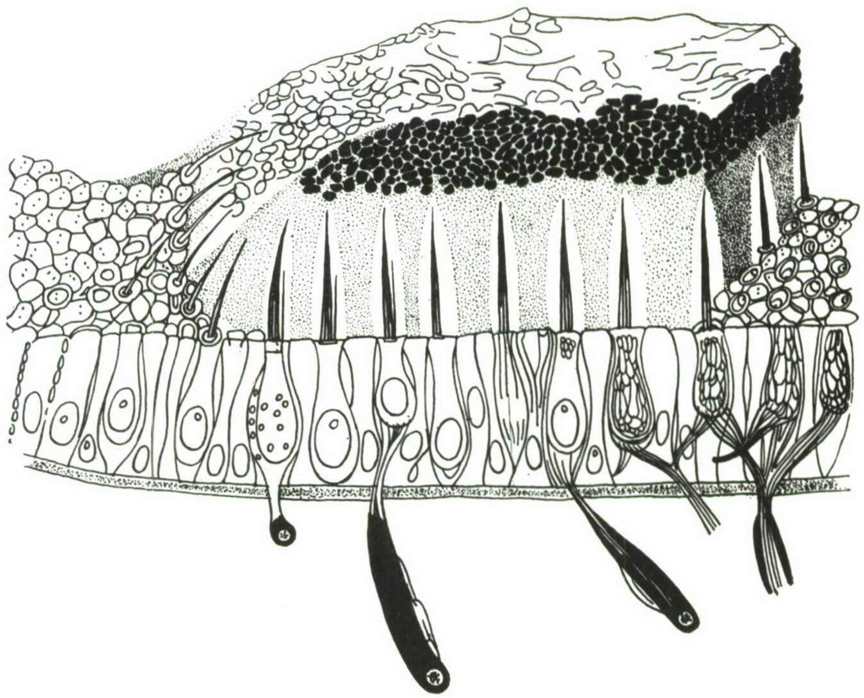
Is it too early to start worrying about the problems of man in space? Indeed it is not. Although the first space flight is not imminent, we are not so very far from the roof of our protecting atmosphere in experimental aviation. Man's newest aircraft, whipped upward by jet and rocket propulsion at breath-taking speeds, are constantly setting new altitude records. Their peak altitudes are a military secret, but one may assume that they fly at heights where the atmosphere is thinning out rapidly. At these highest altitudes, where the domain of space begins, fliers are already approaching the limits of the atmosphere that maintains a convenient climate, provides air for breathing, keeps the temperature within tolerable limits, filters the ultraviolet solar radiation, checks the cosmic rays, burns the meteors and provides the friction that preserves the effects of gravity. The V-2 rocket today routinely ascends to such heights.

In the not-too-distant future intercontinental airliners will probably travel in the thinnest layers of the atmosphere. Powered by rocket engines, the "ionocruiser" will shoot up rapidly until it is in the region of almost no air resistance. Then the engines will be shut off and the craft will fall in an elliptical curve toward its goal. The path of flight will be virtually that of a genuine celestial body, and during the period of coasting the gravity-free state will prevail. The flight of such a craft will closely approximate the conditions ultimately to be encountered in space.

Heinz Haber is a research scientist in the Department of Space Medicine of the U. S. Air Force School of Aviation Medicine.



VESTIBULE OF THE EAR, the sensory organ that maintains the natural position of the head, contains one of the mechano-receptors that would be affected by the absence of gravity. This drawing shows the bony labyrinth of the ear. The cochlea is at right; the vestibule, at left. Within the vestibule is the membranous labyrinth (*indicated in blue*), which bears the receptors.



MEMBRANE OF THE VESTIBULE has regions sensitive to motion. In these regions tiny hairs project into a jelly that also contains relatively heavy particles of the mineral aragonite. When the head is moved, the inertia of the particles is communicated to the hairs. Nerve endings at the base of the hairs then convey impulses to the brain or a reflex mechanism.

RADIATION EFFECTS ON MAN IN SPACE

by

Konrad Buettner

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Radiation Effects on Man in Space *

KONRAD BUETTNER

Department of Space Medicine, USAF School of Aviation Medicine, Randolph Field, Texas

MEDICAL climatology is usually confined to the surface of the earth. So, I must apologize for removing your thoughts from this solid background to elevations where our knowledge is still scarce with regard to the physical facts, and more so concerning possible influences on man.

Besides thermal, photochemical, air-chemical, air-electrical, barometric, and other effects of the environment on man, specific radiations are frequently responsible for biological events. For the time being, we exclude the well-studied thermal effect of solar and terrestrial radiation, as well as photochemical effects such as vision, sunburn, and vitamin D production. We are concerned, instead, with the following four types of radiation and their possible effect on man at any altitude:

(*1.*) Radiation of known characteristics whose effects can be learned from extrapolation, e.g., cosmic ray heavy primaries.

(*2.*) Radiations of known characteristics for which we have some reports on observed effects: cosmic ray showers, solar radio microwaves.

(*3.*) Radiation of known biological effectiveness but of unknown intensity: hard solar x-rays.

(*4.*) An utterly unknown radiation for which effects on man are claimed: Takata reaction.

1. According to Schaefer [1] cosmic ray heavy primaries at altitudes above 20–25 km constitute a hazard to life if exposed for hours. The facts are: these primaries have energies up to 10^{12} volts and an average density at 36 km of 10 particles per m^2, steradian and sec. They are atoms of the atomic number 3–26 or more which lost their electrons entirely. Their specific ionization resembles somewhat the dense tracks of α-particles, but the density is higher and the distance travelled in, e.g., living tissue, has to be counted in cm instead of μ. They never reach the earth's surface but are filtered out by the air above 20 km.

From this, and from comparative data on ionization and damage to living tissues by α-particles and other ionizing radiations, Schaefer draws the following conclusions [1]:

The damage can not be predicted in view of the *r*-units, since the specific ionization is even much larger than that of alpha rays. It is possible, however, to take this into account and, then, compare the cosmic effect with the delayed consequence of radium poisoning which occurs sometimes. It is very important to note how close the natural radioactivity of all living tissue and this lethal radioactivity are. On this basis, the safe time for man at altitudes above 20 km is of the order of hours.

2. Biological experiments with cosmic rays in the Alps, by comparing data in the open and under the shield of a mine, at first, failed. But positive reports were reported by Krebs [2], and Hess and Eugster [3] who put lead shields of about 1 cm of thickness around the samples. Decrease in the number of bacteria, increase in growth of plants from irradiated seeds, higher reproduction rate of flies, earlier onset of artificially induced cancer, etc., are reported.

One to two cm of lead is about the right thickness to produce a maximum value of showers, i.e., numerous clustered particles, all of which originate at the same point in the lead. These showers are held responsible for the described biological effects, but lacking an explanation by the authors mentioned on the specific effects of showers, I deem it difficult to explain them that way, for:—(a) The total ionization expressed in ion pairs cm^{-3} sec^{-1} produced in the air of an ionization chamber is distinctively smaller behind 1–2 cm of lead [4]; the number of showers increasing cannot compensate for the decrease of the total radiation. (b) No radiation originating in the lead is known to be soft enough to be absorbed specifically within the first living cell in its path. This hypothetical component would have to pass the protective coating around the lead first, anyway. A piece of paper inside any lead-shielded ionization chamber reduces the total ionization as much as an equal weight of air would have done [4]. (c) Hypothetically, a specific effect might be anticipated when more than one nucleon strikes the cell nucleus at the same time. We might, e.g., assume that more than one hit has to be applied to be harmful. In the experiments referred to, however, the distance between lead wall and cell was always large enough to let the shower rays spread out. So, in my opinion, we have to leave open the question of shower ef-

* Presented at the 109th national meeting of the American Meteorological Society at New York City on Feb. 1, 1951.

fects (and those are the only cosmic ray effects near the ground that have been investigated).

Cosmic radio microwaves originating in galaxies and on the active areas of the sun, reach the surface in the cm and dm bands. They are known to vary with each solar eruption and one could attribute to these fluctuations some reported correlations of human factors with solar activity. Kiepenheuer [5] tried to explain the parallel question as to the reported relation of sun spots of old age on tree rings widths. The Freiburg botanists observed the mitosis rate of sprouting beans in the field of a shortwave (1.5 m) transmitter having 10^{-14} to 10^{-7} cal cm^{-2} sec^{-1} intensity: Small intensities increase, large ones decrease the cell division rate. The intensity applied is still too large to be compared with that of the sun and the recorded curve is puzzling, but it may be a first step in this direction. (Concerning possible solar effects see also Duell [6]).

3. Glancing over the whole electromagnetic wave spectrum one visualizes the three windows in the filtering atmosphere: for cosmic rays, solar rays, and radio rays. At heights already reached by the V2 rockets, the "dark" areas in between these windows become "bright." From the rays expected and recorded at that height, only hard x-rays may sometimes be of biological importance, since soft x- and extreme UV-rays never penetrate any kind of cover. X-rays in the region above 6 Ångstroms have been found in an amount of approximately 0.1 erg cm^{-2} sec^{-1} [8]. But these are soft, i.e., they do not penetrate below 100 km. On the existence of harder components neither experiment nor theory gives us any reliable hint. Since extreme UV- and soft x-rays are known to vary strongly with the solar intensity, this lack of knowledge does not exclude the existence of hard x-rays.

4. Now we come to a mysterious radiation whose existence has been claimed on the mere grounds of biological experiments. These are the facts: A leading Japanese physician, M. Takata [7], observed fluctuations of the so-called "Takata reaction" in blood of healthy males which show a good correlation with solar activity. This reaction is similar but not identical with the "Takata-Ara Test," now widely used for diagnosis of liver trouble. The blood serum of healthy males only can be used for these experiments, since in females the monthly cycle influences the readings. The test consists in adding increasing amounts of sublimate, $HgCl_2$, plus fuchsin and buffer, until fine needle-like flocculi, a precipitated linear-chain protein, can be seen. The reported radiation influences on this serum to be described take place only *in vivo*.

Takata [7] observed in sera of several male persons in Japan, that:

(a) The flocculation number was constant from 1935 to 1938; from 1938 to 1943 the data showed a strong scattering from day to day and, generally, an increase (—increase means that more reagent has to be added). In 1943 the data returned to "normal" (1935–38 levels).

(b) Day values are higher than those of blood extracted at night.

(c) People in a mine showed lower values than those on the surface as did people during a solar eclipse.

(d) The count increased from 76 to 91 while climbing up Mt. Fujijama (3,697 m) and by more than 100 percent in two airplane flights up to 7.2 km msl. Control experiments in a pressure chamber with the same three men using the equivalent oxygen fluctuations were negative.

(d) Large doses of x-rays, γ-rays and neutrons also raised the count. UV, sunlight, ultra-short waves, and exercise were ineffective.

(f) Electrostatic charging of the insulated human body and the inhalation of large ions influence the count.

From these results Takata postulates the existence of an ionizing, penetrating solar radiation.

Biological findings alone have rarely successfully demonstrated unknown physical factors (—one recalls the "mitogenetic radiation" reported by Gurwitsch some 20 years ago). Reissmann, Buettner and Topka [9] therefore repeated the Takata experiments. If the original results were related to the 1940 sun-spot maximum, our results should be related to the recent (1950) maximum. At any rate, the Zurich sun-spot numbers were high during our series. After some correspondence with Dr. Takata, Dr. Reissmann was able to reach nearly the same accuracy in blood testing that Takata claims to achieve. Generally speaking, our technique was workable and accurate enough for the purpose of checking Takata's results.

We obtained the following results from an 8-months series of tests with 4 men as subjects:—No variation in counts with time could be found and therefore no correlation with sun spots seems to exist in Texas, as the sun-spot number varied between 40 and 220. No day-night difference was detected, nor any influence by an electric charge up to 510 volts. Airplane flights up to 9,000 m in a pressurized cabin and to 6,000 m breathing oxygen (sun-spot numbers 108 and 71,

respectively) did not affect the flocculation count either, except for a decrease in one man who became airsick during the second ascent.

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ON THE PHYSICS AND PSYCHOPHYSICS OF WEIGHTLESSNESS

by

Heinz Haber and S.J. Gerathewohl

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AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Physics and Psychophysics of Weightlessness

By H. Haber, Ph.D., and S. J. Gerathewohl, Ph.D.
USAF School of Aviation Medicine, Randolph Field, Texas

THE DEVELOPMENT of aviation is directed toward ever increasing velocities and altitudes. Already, today, aircraft fly at altitudes at which the density of the atmosphere is extremely low. According to the principles of mechanics, reduction or entire lack of weight will ensue during coasting maneuvers at high altitudes because mechanical support by the atmosphere is lacking.[5] Consequently, the pilots of rocket aircrafts will have to familiarize themselves with the occurrence of sub-gravity and zero-gravity states.

In these states, little or no forces are exerted on the airman, causing him to experience little or no sensations of weight. Whereas the physiological and psychological effects of gravity greater than 1 g have been widely studied, and the tolerance limits for men under various conditions of positive and negative acceleration have been determined, little is known as to human behavior under conditions of reduced gravity. With the development of high-altitude, high-velocity flying, however, physiological and psychological functions in the sub-gravity and zero-gravity states will become a major subject for research. This paper attempts to delineate some of the physical and psychophysical problems associated with the lack of gravity.

PHYSICS

Within the gravitational field of the earth a body derives its weight from the mechanical support that prevents it from falling freely. The forces experienced by the body expressing themselves as weight become evident only if the body is supported. If a body moves vertically downward with an acceleration of 1 g, i.e., after having lost its support and falling freely[1,5] with a constant acceleration, an upward pulling force of inertia becomes effective, which exactly eliminates the body's weight. In this case, the body will find itself in the *zero-gravity* state. If a downward directed, constant acceleration smaller than 1 g is applied, the upward pulling force of inertia will not entirely abolish the body's weight. In this case the body is in a state of *sub-gravity* of a certain amount.

In applying these principles to the human body, another mechanical factor, elasticity, must be taken into account. Hence, the behavior of an elastic body (a rubber ball for instance) under conditions of normal gravity and zero-gravity will be discussed.

As already mentioned, this rubber ball has weight only when it is supported. As a consequence of the forces associated with this support, a certain field of elastic forces is generated on the surface and in the interior of the body. Consequent to the process of placing the body onto its support, an elastic deformation takes place. This deformation is characterized by a state of equilibrium between

the elastic forces within the body and the gravitational forces.

The gravitational forces which act on each individual molecule of the body are eliminated by the forces of inertia as soon as the body moves along a Keplerian trajectory with respect to the center of attraction. In the latter condition, the body finds itself in the gravity-free state. The transposition into this state brings forth a change in the above-described field of the elastic forces in the interior and on the surface of the body. This field of forces attains a new state of equilibrium which depends solely on the structural elements of the body, such as elasticity, shape, and material constitution, and which is characterized by the condition that the sum of all elastic forces acting on each point of the interior and the surface of the body vanishes. These conditions hold as long as the body is at rest or moves at a constant velocity relative to the gravity-free system. In all cases of accelerated motion, however, forces of inertia become effective and play the role of a quasi-gravity. The conditions involved in these phenomena can most easily be demonstrated by means of a hypothetical experiment.

It is assumed that the elastic body is suspended in a system of springs and subjected to a plain sinusoidal motion under conditions of zero-gravity. The mechanical characteristics of the springs, the proper frequency of the system, the conditions of excitation, and the amplitude may be such that the acceleration peaks amount to ± 1 g. Frictional forces are neglected. As is known, the kinematic and dynam-

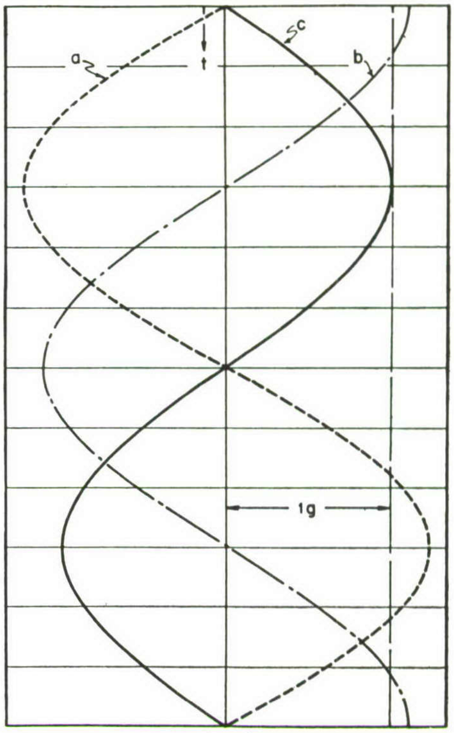

Fig. 1.

ic conditions can be described by the equations

$$s = a \cdot \sin(\omega t - \Phi) \tag{1}$$

$$\frac{ds}{dt} = v = a \cdot \omega \cos(\omega t - \Phi) \tag{2}$$

$$\frac{d^2s}{dt^2} = b = -a \cdot \omega^2 \sin(\omega t - \Phi) \tag{3}$$

in which $s =$ the distance of the body from the zero point, $a =$ amplitude, $\omega =$ frequency, $v =$ velocity, $b =$ acceleration, $\Phi =$ phase constant, and $t =$ time. The three functions are demonstrated graphically in Figure 1 (a, b and c). As can be read from Figure 1 (c) and from equation 3, the body is subject to forces varying in a sinusoidal way. These forces provide the body with its full weight at the peaks of acceleration. At the zero points the

body finds itself in the gravity-free state for an infinitesimal period of time. It may further be pointed out that the body experiences a periodic change in the direction of the quasi-gravity. It follows from these conditions that the elastic body is subject to periodic elastic deformations, since the forces at play are invariably pulling outward, away from the zero line.*

The aforementioned consideration concerning the behavior of an elastic body under conditions of 1 g and zero-gravity will be taken as a basis for an analysis of the psychophysical phenomena associated with the gravity-free state.

PSYCHOPHYSICS

In theorizing on the psychophysical phenomena related to the gravity-free state, one has to consider that the human body is also an elastic body. One must be aware, also, that the human body, with its system of mechanoreceptors, possesses an instrument that provides information as to the forces acting on or within the body. Among the mechanoreceptors one discerns the following ones: (1) vestibular apparatus consisting of the semicircular canals, utriculus and sacculus as receptor organs for rotary and translatory motion; (2) the basket-like nervous plexuses around the hair follicles and the Meissner corpuscles as the receptor organs of the pressure sense of the skin; (3) the muscle spindles as the receptors of the myotatic reflexes and of the muscle sense, and (4) the Vater-Pacini corpuscles as receptors of the posture sense.**

In the following the function of the semicircular canals is not considered since the discussion is centered chiefly around the effects of translatory accelerations. The behavior of an elastic body under the various conditions previously described is now applied to the human body.

There are five different cases to be considered:

1. Under normal conditions (g = 1), at rest or at a constant velocity.
2. Under normal conditions in accelerated motion.
3. Within a gravity-free system at rest or at a constant velocity.
4. Within a gravity-free system with involuntary accelerated motion of the body.
5. Within a gravity-free system with voluntary accelerated motion.

The above five cases will be discussed in detail as follows:

1. *Under Normal Conditions (g = 1), at Rest or at a Constant Velocity.*—Since we find ourselves almost invariably in a fully supported state (standing, sitting, lying on a support), the state characterized by 1 g must be considered the normal mechanopsychophysical state of the body. This condition is taken by the individual as the static zero state in which no sensations of force and acceleration

*Under conditions of 1 g such changes in direction of "weight" can only be realized if the body is moved downward at an acceleration greater than 1 g. Such conditions, however, can hardly be realized for any length of time, so that these changes in direction of "weight" could not manifest themselves psychophysiologically.

**For a detailed compilation concerning the mechanoreceptors of the skin and muscles, see H. Strughold.[6]

are normally experienced. In terms of physics or more specifically of mechanics, the body is then in a certain state of mechanical tension. As is the case with any elastic body, within the human body there is a field of elastic forces which carries the weight of the body and its parts. Depending on the spatial position of the head in the position of rest, the end organs of the sacculus and urticulus are stimulated in a certain manner. This is brought forth by the weight of the otoliths and the membrane of the otoliths which elastically deform the epithelial hairs by pressure, pull, or shearing. Furthermore, the weight of the body and its parts rests upon the supports; this leads to a stimulation of the end organs of the pressure sense at the contact areas of the skin. This stimulation is equally produced by the elastic deformation of the respective parts of the body. The specific stimulus for the sensory nerves of the pressure sense is not pressure as such, but change in pressure. This is the reason why an extremely fast adaptation to the prevailing state of tension on the surface of the body is observed.

The receptors of the muscle sense experience a stimulation which also stems from the general field of elastic forces found within the body.

In this connection it may be pointed out that, among the four sense modalities mentioned, only the pressure sense is distinguished by a pronounced objectivation. In contrast to this, the function of the sacculus and utriculus as well as the muscle sense and the posture sense are more closely linked to the reflex mechanism of the body. Nevertheless, muscle sense and posture sense can be somatized to such an extent that the sensations provided by these senses can become conscious.

2. *Under Normal Conditions in Accelerated Motion.*—The inner field of elastic forces, which prevails within the body at rest under 1 g, is changed in a certain manner by any voluntary and involuntary accelerated motion. These changes effect a pattern of stimulation of the mechanoreceptors that, as a whole, is accompanied by sensations of moving and/or being moved.†

3. *Within a Gravity-free System at Rest or at a Constant Velocity.*—The weight of the body and its parts vanishes under conditions of zero-gravity. At the same time that component of force which causes the gravitational deformation of the body vanishes also. Similar to the above-mentioned elastic body, the human body, in the gravity-free state, will build up an inner and outer field of forces, in which the sum of all elastic forces acting on all points of the body vanishes. In transposing the human body into this new state of equilibrium the stimulation of the mechanoreceptors is altered decisively. The otoliths and membrane of the otoliths, deprived of their weight, do not exert any pull or pressure on the end organs of their respective sense apparati. The stimulation of the receptors of the pressure sense generally vanishes, since the body does not require any support (i.e., there is generally no

†It must be considered that these additional forces can only be small relative to gravity, which is constant as to direction and size. Forces surpassing gravity to a great degree exist for only extremely limited periods of time as in shocks.

contact with any foreign body). In the gravity-free state the body and its parts can do without any outer elastic force to carry the weight. The tonus of the muscles in a general rest position under these conditions depends solely on those forces which stem from the field of elastic forces based on the natural cohesion of the body's parts. The receptors of the muscle sense will be placed under a stimulation that cannot be realized under conditions of 1 g.

The receptors of the posture sense experience hardly any noticeable change. These receptors are localized chiefly in the connective tissue of the muscles and the tendons that have little elasticity. Elastic deformations of this tissue are caused far more by posture and movements of the limbs than by changes in weight.

A stimulation of the mechanoreceptors, as a whole, can be experienced only in the situation of falling freely.

The sensations associated with the free fall are chiefly characterized by the impression that all support is giving way from under one. In fact, the sensation of falling can almost be identified with this kind of experience. It may further be pointed out that the above-described stimulation of the system of mechanoreceptors is accompanied by a number of motor reflexes such as statokinetic reflexes of the limbs, innervation of the muscles of the neck, reflexus vestibulo palpaebralis, etc. These reflexes are typical for sudden-fall reactions and other abnormal reactions of the mechanoreceptor system.

Nothing is known, by nature, of the adaptability of the individual to the situation of falling freely. The possibility or even probability of such an adaptation, however, may be presupposed as a working hypothesis for the following discussions. This hypothesis is identical with the statement that the above-described field of elastic forces of the body at $g = 0$ is taken by the individual as a new psychophysical zero-state.

4. *Within a Gravity-free System with Voluntary Accelerated Motion.*—In analyzing the conditions associated with the involuntary accelerated movement at $g = 0$, the human body may be subjected to the beforementioned experiment. Considering the possible adaptation to the gravity-free state one must distinguish two different cases: (1) the individual being adapted to the condition $g = 1$; (2) the individual being adapted to the condition $g = 0$.[7]

In the first case it is assumed that the test subject is an individual unadapted to the gravity-free state. The state of adaptation to the conditions of $g = 1$ is supposed to last for the duration of the hypothetical experiment. It is further assumed that all other sensory stimulations—especially of the eye—are excluded. The longitudinal axis of the subject's body is oriented parallel to the oscillatory movement. The forces acting on the body under these conditions can be read from Figure 1(c); i.e., the mechanoreceptors will be placed under a stimulation that varies periodically as to size and direction. It can easily be seen that the peaks of acceleration occur at the turning points of the motion, reaching the amount of $\pm$ 1 g

according to the example. It is at this place that one must recall that man possesses an orientational scheme related to position and motion. This scheme is, to a large extent, based on the action of gravity. According to this scheme the direction "down" is identical with the direction of gravity. In the hypothetical experiment we are dealing with accelerated motion and consequently with the occurrence of quasi-gravity stemming from the forces of inertia. As mentioned before, this quasi-gravity is invariably pulling outward, away from the zero line, while it vanishes in the zero position. As has been the case with the elastic body previously described, the subject's body will undergo elastic deformations, which are accompanied by a corresponding stimulation of the mechanoreceptors.

A full period of the motion is subdivided into four phases which are designated by I, II, III, and IV in the graph of Figure 2. This graph gives the locus of the subject as a function of time. At the point A the subject finds himself in the gravity-free state for an infinitesimal period of time. Consequently, in the beginning of phase I one has to anticipate a fall sensation. The "fall" of the subject will subsequently be "braked" in approaching the point B.‡ Since, at the point B, the acceleration attains the value of 1 g the subject may possibly have the sensation of having been "braked" to a standstill. In this instant the subject can interpret this situation as being suspended and fully supported by the straps in the normal position

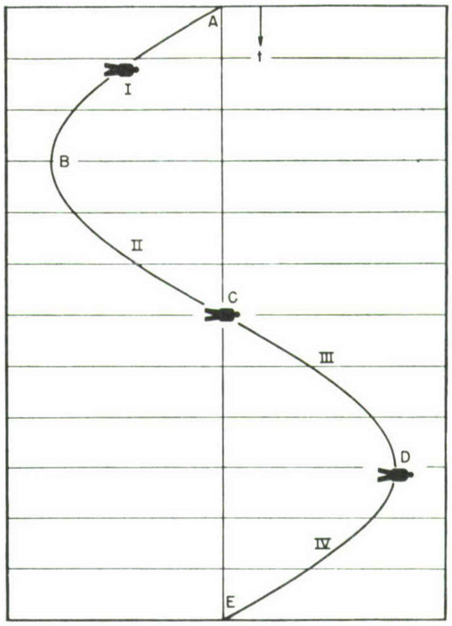

Fig. 2.

(feet downward).

During the phase II the conditions of phase I are reversed. In the beginning of phase II the pressure of the straps begins to decrease. Consequently one has to expect a sensation associated with a transition from a fully supported state into the state of falling freely. The latter is reached at the point C where, with g = 0, any fashion of support vanishes. During the phases III and IV the same phenomena are repeated, with the difference that during these phases the subjective direction "down" is localized in the direction of the head. From this it can be concluded that, during one full period, the subject experiences a conversion of his bodily position relative to his subjective "down" direction. Under normal conditions of 1 g, such a phenomenon cannot be experienced unless the subject is turned around.

‡Quotation marks indicate the sensations experienced by the subject.

It must be pointed out that the phases III and IV (head down) will be accompanied by more pronounced sensations since the end organs of the sacculus and utriculus show much stronger reactions to pull than to pressure. One can therefore expect that this kind of motion will be experienced as highly asymmetrical.

In dealing with the second case (a subject adapted to the conditions of zero-gravity) it can be expected that the sensation of falling freely at the points A, C, and E has vanished. An individual adapted to this state will experience a sensation of rest in the gravity-free state. In this it must be considered that, at $g = 0$, every additional force acting on the body and on the mechanoreceptors will be experienced as a force and will be accompanied by a feeling of being moved. This contrasts to the conditions of $g = 1$, when a continuously acting force (namely, gravity) is associated with the sensation of being at rest. Consequently it can be assumed that an individual adapted to $g = 0$ will experience a lift sensation when transposed into the natural state of $g = 1$. This sensation will prevail until the subject is readapted to the normal state. Returning to the hypothetical experiment one must assume that the subject has a sensation of rest at the point A. In approaching the point B the pressure of the straps increases, the end organs of the vestibular apparatus are stimulated by pressure so that the subject will experience an increasing sensation of lift, head "up." This sensation of lift reaches a maximum at the point B, decreases during phase II and vanishes at the point C. During the phases III and IV these sensations are repeated, yet, with the difference that the subject experiences a corresponding sensation of lift, feet "up."

5. *Within a Gravity-free System with Voluntary Accelerated Motion.*—The body and the limbs cannot be moved voluntarily without being accelerated. As long as these accelerations last, one will observe an elastic deformation of the body and its parts and, consequently, the stimulation of the mechanoreceptors will be altered.

Movements of the whole body as they occur if one moves voluntarily will be discussed first. The conclusions arrived at in the discussions of the before-mentioned hypothetical experiment can immediately be applied; only the case of an individual adapted to $g = 0$ may be considered.

An individual may be at rest at the point A and may subsequently change his place to come at rest again at the point B. The subject can accomplish this by either pushing himself away from the point A or by pulling himself in the direction of the point B, using a handle or a similar device. While being accelerated away from the point A, the subject finds himself in a situation similar to that prevailing in the phases I and II of the experiment mentioned last. Consequently, the subject experiences sensations of lift (head "up") during the acceleration period. The subject finds himself again in a gravity-free state while floating from the point A towards the point B. At the point B the subject brakes the motion by stemming off the wall or another object, with his hands. The deceleration arising in this proc-

ess stimulates the mechanoreceptors in such a manner as observed during phases III and IV of the experiment mentioned above. During the period of deceleration the test subject experiences the sensation of lift (feet "up"). From an analysis of this process the following remarkable phenomena associated with voluntary alterations of one's place can be derived: During the state of rest at the point A, no directions distinguished as "up" and "down' exist. The six boundary surfaces of the ambient room are all "walls"; floor and ceiling are defined solely by convention. During the phase of acceleration the wall bearing the point A becomes "floor." During the phase of floating, i.e., while the subject moves at a constant rate of velocity between the points A and B, the same state as experienced at rest prevails. During the phase of deceleration the wall bearing the point B becomes "floor," against which the subject stems with a "handstand." Similar to the hypothetical experiment, voluntary alterations of one's place involve a subjective tilting "up-down" by 180°. It must be added that the end organs of the semicircular canals are also stimulated in almost all cases of voluntary and involuntary movements. These stimulations vary strongly, depending on the posture of the head relative to the direction of acceleration and deceleration. The occurrence of illusions of being rotated and a corresponding activation of the reflexes coupled with the stimulation of the semicircular canals cannot be excluded.

In moving the limbs voluntarily under conditions of zero-gravity one will observe a disturbance of the co-ordination of the relative stimulations of the end organs of the muscle sense and the posture sense. Lifting the arm at $g = 1$, for instance, requires not only overcoming of the arm's inertia but also of the arm's weight. In each position of the arm, a certain stimulation of the posture sense is co-ordinated with a certain stimulation of the muscle sense. Under conditions of zero-gravity this co-ordination is disturbed, since the arm has no weight and only the arm's inertia must be overcome in moving it. This means that the stimulation of the muscle sense must change while the stimulation of the posture sense is virtually equal to that prevailing under conditions of 1 g. This phenomenon will produce a dissociation of the normally concerting sensations of the muscle sense and the posture sense.

The entire range of phenomena discussed so far is related to the stimulation of the mechanoreceptors alone. Other perceptual cues, especially visual ones, are excluded. It must be expected that including the eye into the stimulus-sensation mechanism will decisively alter the picture. It can be assumed that use of the eyes will be of considerable help in overcoming the sensation of falling freely subsequent to a transposition into the gravity-free state. For, a visible movement of the body relative to its surroundings does not exist, contrary to the fall situation on earth.

The sensations of the individual associated with the swing experiment described above may also be modified decisively if the subject is not blindfolded. It can be assumed that the in-

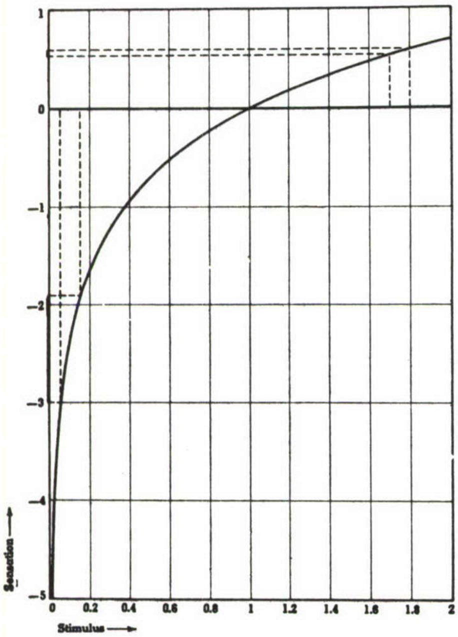

Fig. 3.

dividual will be able to identify correctly the oscillatory movements by a visual evaluation of his kinematic situation. In this, training, experience, and intelligence will play a part. As is known, for instance, a beginner perceives the horizon as tilted during sharp turns of an aircraft, while an experienced flyer is able to maintain the ground as a horizontal reference plane even during complicated flying maneuvers. Virtually at all times, the experienced flyer can identify objectively his position and motion relative to the ground. By the use of his eyes man can learn to suppress the false information given by the mechanoreceptors. Campbell[2] (1950) has specifically pointed out the importance of this phenomenon in relation to the problem of orientation in the gravity-free state.

While considerable help in the situation of zero-gravity can be expected when visual cues are included, another phenomenon pertaining to the functions of sense organs must be considered as an aggravation. This aggravation is based on the Weber-Fechner Law (Gauer).[3]

The Weber-Fechner Law, as is known, describes the relation between the intensity of a stimulus and the intensity of the co-ordinated sensation. Mathematically speaking, this law maintains that the intensity of the sensation is proportional to the logarithm of the corresponding stimulus. We are led to assume that this law holds also for the function of the sense of gravity, though the sense of gravity is a complex structure composed of the function of the vestibular apparatus, of the pressure sense of the skin and of the proprioceptors of the muscles. As mentioned before, the assumed validity of the Weber-Fechner Law for the gravity-sense leads to earnest consequences in view of the gravity-free state. In regard to this see Figure 3. This figure demonstrates the simple logarithmic curve, $y = \log \text{nat } x$, whence x represents the stimulus and y the corresponding sensation. The logarithmic curve intersects the x-axis at the value $x = 1$ and approximates the value $y = \infty$ for $x = \infty$; for $x = 0$ the value of the logarithm becomes $y = -\infty$. The relation between stimulus and sensation is fairly well represented by the central part of the logarithmic curve, as far as the well-investigated senses are concerned. The values $x = 0$ and $x = \infty$, however, are not realized biologically; there, caused by the absolute threshold and

the pain threshold, respectively, natural limits of the function of the sense organs are imposed, resulting in certain deviations from the ideal logarithmic relation. The value $y = 0$ for the sensation does not indicate that no sensation prevails for the stimulus $x = 1$; the value $y = 0$ must be defined as a sensation corresponding to a mean intensity such as will be found for the eye at normal room illumination (50 to 100 foot-candles), for the ear at a mean noise level (40 to 50 db). In our case, the sensation of gravity which corresponds to the value $y = 0$ may be set equal to the sensation which is registered at a gravity of 1 g.

The curve which represents the Weber-Fechner Law exhibits an important factor. A range of sensations covering the section from zero to infinity corresponds to the range of stimuli from $g = 1$ to $g = \infty$; a range of sensations covering the section from zero to minus infinity corresponds to the range of stimuli from $g = 1$ to $g = 0$; consequently, if we reduce gravity from $g = 1$ to $g = 0$, we cover a range of sensations which is as large as the range of sensations corresponding to an infinite increase of acceleration starting from $g = 1$. The function of the gravity sense becomes particularly critical in the proximity of $g = 0$. As can be read from the curve, strong sensations are caused by minute changes of acceleration, if man is subjected to states of gravity close to zero. Yet, accelerations of critical amounts are already produced by voluntary and non-voluntary body movements accompanied by correspondingly strong sensations of acceleration at $g = 0$. At $g = 1$, such small additional accelerations are below the threshold according to the Weber-Fechner Law. At this time there is no way of knowing how the co-ordination of the optical sense and the mechanoreceptors at the peak of their sensitivity will work.

The analysis of the presumable psychophysical phenomena in the gravity-free state had, by necessity, to depend on assumptions and conclusions by analogy. Here, only the experiment will decide. It is intended to outline in a second paper[4] the specific psychological problems associated with the zerogravity state.[5]

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WHERE DOES SPACE BEGIN? Functional Concept of the Boundries Between Atmosphere and Space

by

H. Strughold and Heinz Haber

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SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Where Does Space Begin?

Functional Concept of the Boundaries Between Atmosphere and Space

By Hubertus Strughold, Heinz Haber, Konrad Buettner and Fritz Haber

Department of Space Medicine, USAF School of Aviation Medicine, Randolph Field, Texas

In speaking of "space," one commonly refers to it as a topographically defined system. In this sense, the borders of space in relation to the earth are identified with those regions where the last traces of air become lost in the void, i.e., 400 to 800 km. (250 to 500 miles) above the earth's surface; or, the borders of space are occasionally interpreted as that zone where the terrestrial field of gravitation is so reduced as to be insignificant. However, "space" as a topographical concept is misleading when used in discussions related to manned rocket flight.[2] Rather, these problems must be treated on the basis of the functions which the atmosphere has for man and craft. In this regard the atmosphere fulfills three important functions:

1. The function of supplying breathing air and climate,
2. The function of supplying a filter against cosmic factors,
3. The function of supplying mechanical support for the craft.

Each of these three functions has a technical as well as a medical aspect. These functions lead us to a new concept of space which is more adequate to the peculiarities of manned rocket flight than is a topographical interpretation of space. In that which follows, this functional definition of space will be discussed briefly with special emphasis on the space medical aspects.

The Function of Supplying Breathing Air and Climate

Breathing Air. — Through experiments on explosive decompression we obtain quantitative information as to the extent to which the atmosphere can maintain the oxygen supply of the body. In those experiments a subject is transposed, within fractions of a second, from a state of normal oxygen supply to a state of oxygen want such as would be found at higher altitudes. Because the stratosphere has become accessible through the rapid development of aviation in recent times, such explosive decompression experiments have been performed in great numbers. The results of the experiments which are of interest in our case may be related briefly, wherein technical and physiological details are omitted.

If a subject is brought abruptly from normal oxygen pressure to that found at 8000 meters (26,000 feet) the first psychophysiological disturbances can be observed after a period of about two minutes; after another minute the subject becomes entirely helpless, falling into a critical phase (loss of consciousness). The time span, during which he is still capable of acting is called the "time of useful conscious-

ness,[1] or the "time reserve."[24] This characteristic time span is reduced to 80 seconds at 9 kilometers (29,500 feet), to 50 seconds at 10 kilometers (33,000 feet), and finally to between 15 and 11 seconds at about 14 kilometers (46,000 feet).[3,7,9,16,18,20,21] At this point a decisive limit is reached. At still higher altitudes the time reserve remains constant, as was proven in experiments up to 17 kilometers (56,000 feet).

Experiments have shown that this minimum time reserve of about 13 seconds is reached at 16 kilometers (52,500 feet), if oxygen, instead of air, is breathed prior to explosive decompression.[3] However, this is a mere experimental variation. The essential point is that the time reserve attains a minimum limiting value at an altitude of 14 kilometers (46,000 feet), and, in the extreme case, of 16 kilometers (52,500 feet). We have to expect the same anoxic time reserve of about 13 seconds in case of a rocket ship, cruising outside the atmosphere, being destroyed completely by the impact of a meteor. This means that, from the viewpoint of respiratory physiology, the borders of space are found at an altitude of about 16 kilometers or 10 miles. It is at this height that the atmosphere's function of supporting the oxygen supply vanishes. The constant time reserve observed at this altitude acquires the rank of a physiological time reserve of space.

The same line of thought can be applied, in principle, to other phenomena such as "survival time" and "revival time" which were studied in detail in animal experiments.[10,19,22] We are concerned primarily, however, with time reserve because it is the most obvious example.

The boiling point of body fluids in relation to ambient pressure is another significant factor which merits consideration. According to experimental investigations, the boiling point is reached at an altitude of approximately 20 kilometers (65,000 feet).[1]

Another problem related to the atmosphere's complex function for respiration will be mentioned briefly. It is the problem of "bottled air." It has been computed that, above a certain altitude, breathing air for the ship's crew can no longer be derived from the ambient air. The low air density would require large compression pumps and bulky radiators for the air which is being heated by the necessary compression. At a certain altitude, this equipment would have to be so cumbersome as to be prohibitive. There, the ship would depend as much on "bottled air" as in actual space. In addition, at an altitude of no less than 20 kilometers (12 miles) the ozone concentration in the ambient air is so high as to exceed the toxic threshold after compression. As is known, in these layers, ozone is generated photochemically.

Climate.—In discussing the atmosphere's function of providing a suitable climate, we confine ourselves to temperature as the most characteristic climatic factor. In the denser layers of the atmosphere the temperature inside an aircraft is chiefly determined by the exchange of heat between the ship's hull and the ambient air. Owing to adiabatic and friction heating the process of heat exchange between ship and air is dependent on velocity.

Above a certain altitude the heat transfer between the atmosphere and the ship becomes negligible. From then on the ship's temperature will be determined solely by the exchange of radiation between the ship's exterior on the one side, and the sun, the earth, and cosmos on the other.[4,5] Depending upon the incoming radiation and the spectral reflectivity of the hull, a certain equilibrium temperature will result.

For a body at rest in relation to the ambient air (balloon), the conditions of pure radiation climate are practically fulfilled at an altitude of about 20 kilometers (12 miles). This limit is found at even greater heights with increasing velocity of the body. The upper altitude limit, where atmospheric heating plays the major role in determining the ship's hull temperature, lies at 150 kilometers (90 miles) for average meteoric speeds. An aircraft cruising at presumable operational speeds will find itself in the state of pure radiation climate at altitudes ranging from 40 to 50 kilometers (25 to 30 miles).

THE FUNCTION OF SUPPLYING A FILTER AGAINST COSMIC FACTORS[5]

A large number of physical factors display themselves in extraterrestrial space. The most important of these factors are listed below in the order of their significance.

(a) Solar radiation (visible, heat, ultra-violet, x-rays, radio waves).
(b) Cosmic rays (protons, heavy primaries).
(c) Meteors

These factors differ considerably in their physical nature. Consequently, one must expect that, in meeting and traversing the terrestrial atmosphere, these factors will react in the most diverse fashion. Especially, we will find that the rate of conversion which these factors suffer in the atmosphere will be quite different for each factor. The extent of this conversion will depend greatly on the altitude. These considerations permit us to define functional borders of space by evaluating the filter effect of the atmosphere for each single factor.

Solar Radiation.—On a bright day the visible part of the solar spectrum is the only radiation capable of reaching the ground practically unimpaired.[12] More than 90 per cent of this radiation may occasionally pass the entire atmospheric filter. The blue of the sky that owes its appearance to the scattering of visible light through the action of air molecules. The brightness of the daylight sky decreases gradually with increasing altitudes and finally fades into the blackness of space. At an altitude of about 120 km (75 miles), the sky is as dark as that of a moonlit night at sea level. The last traces of daylight have vanished at an altitude of about 150 km (95 miles).

The infrared parts of solar radiation are affected to some extent by the absorptive action of water vapor, though the bulk of the extraterrestrial infrared radiation of the sun reaches down to the ground. So far as visible and infrared radiation from the sun are concerned, the earth's surface can be taken as the border of space.

Solar radio waves, up to a certain wave length (50 centimeters), i.e., the microwaves, pass the entire atmosphere without any appreciable loss in

intensity, whereas longer electromagnetic waves (> 50 centimeters) are almost entirely reflected back into space by the ionosphere. These waves could be observed at extremely high altitudes only.

The erythema-producing parts of the solar ultraviolet spectrum are almost entirely blocked by the ozone layer extending between the 15 and 30 kilometer levels (9 and 18 miles). Above this altitude erythema of the skin and eyes could be produced in one-tenth the time required to produce the same effects at sea level. From the standpoint of erythematic effects of ultraviolet radiation, the conditions to be encountered in space exist at altitudes as low as the upper border of the bulk of the atmospheric ozone.

Proceeding to still shorter wave lengths the photoelectrical and photochemical effectiveness of the radiation becomes greater. Consequently, lesser air equivalents are necessary to cut off these radiations. This means in terms of our concept that the borders of space lie higher and higher when proceeding from ultraviolet radiation to soft x-rays. No trace of such radiation can be observed even at a height of 100 km. (60 miles). Only hard x-rays could again reach farther down into the 50 kilometers (30 miles) region, but they have not yet been observed. This does not disprove their existence, since solar radiation of this kind must be expected to vary extremely as to intensity and it will most probably be confined to brief periods of time (short time solar activity of isolated areas on the sun's surface).

Cosmic Radiation.—The primary particles of cosmic radiation cause extremely complex secondary and higher order nuclear events in colliding with the nuclei of the air atoms and molecules.[15,17,23] Practically no cosmic primaries reach the ground. In view of our concept we can omit the complexities of the secondary reactions and confine the discussion to the question at what altitudes an appreciable percentage of the original primaries, as they traverse space, may be found.

The frequency distribution of the cosmic primaries in atomic species (H:He:Heavier Elements — 0.79:0.20:0.01) can be expected to correspond roughly to the cosmic abundance ratio of the elements. Owing to the tremendous energy of the primaries (~ 2 BeV per nucleon), they are characterized by an enormous energy dissipation in passing through matter. This energy dissipation is greater, if the kinetic energy of the individual particle is greater. Consequently, the lower limits to which a certain percentage of the primaries can penetrate exhibit a certain stratification according to atomic number and energy of the particles.

About one-half of the primary protons penetrate down to an altitude of approximately 20 kilometers (12 miles). The lower limit of the heavy primaries is about 21 kilometers (13 miles). Above this altitude their number increases considerably, while the heavier ones appear in the order of their weight and energy. Concerning the biological effects[23] of the primary cosmic particles one has to expect them to act similarly to radiation of the alpha particle type: quick energy dissipation with a correspondingly high concentration of ion pairs produced along short

tracks. For the practical case it has to be considered further that man will not be exposed directly to the cosmic primaries but will be protected by the ship's hull. A protective screen that would absorb the heavy primaries entirely would have to be so thick as to be prohibitive for any self-propelled ship.* A certain amount of the heavy primaries would have to be absorbed by the passengers. In addition to this, bursts of secondary particles and γ-rays originating in the walls will find their way into the interior of the ship. Experiments on the biological effect of secondaries have been made by the use of optimal shielding above the specimen. It appears that certain biological effects can be produced under these conditions.[17]

Summing up, one can state that, from the standpoint of cosmic radiation, the borders of space are reached at the altitude of about 30 kilometers (18 miles).

Meteors.—The atmosphere absorbs meteors of virtually all sizes. Only the larger ones are capable of reaching the ground. The problem of meteors is a serious one, in view of possible collisions between a ship cruising at highest altitudes and these specimens of stray cosmic matter. Because of the considerable average velocity of the meteors (20 to 60 kilometers/seconds), (12 to 36 miles/seconds), such a collision would be catastrophic if the meteor involved exceeds a certain mass. In hitting a ship a meteor would instantaneously transform the major part of its kinetic energy into heat, vaporizing the steel of the hull at the point of impact to a greater or lesser degree.

Because of their tremendous velocities most meteors are vaporized and annihilated at great altitudes. The impact of atmospheric molecules and atoms upon the surface of the meteors and, in the denser layers, adiabatic and friction heating are responsible for the fast vaporization of the meteors. The event of a vaporizing meteor displays itself as a shooting star.

The great majority of meteors ranging between fine meteoric dust and particles weighing a gram or more, are annihilated before reaching the 80 to 90 kilometer level (50 to 56 miles). Occasionally meteors become visible at more than 150 kilometers (90 miles) above the earth's surface; most commonly, however, they appear at an altitude of 110 kilometers (70 miles). Above that altitude, those meteors which are a potential danger to space craft still have the bulk of their original kinetic energy.

THE FUNCTION OF SUPPLYING MECHANICAL SUPPORT

Since a lack of weight is an outstanding factor of environment in present and future flights in the upper atmosphere and in space, it is appropriate to discuss the phenomena of weight and weightlessness in relation to our problem.[6,8,11,13,14] It can be shown that these phenomena are governed by the interplay of gravitation, inertia, and outer forces related to the atmosphere.

The kinematic and dynamic conditions of a body moving in space are

*Contrary to the case of a self-propelled ship it would be thinkable to provide shielding for the crew of an artificial satellite.

characterized by the lack of friction, since any mechanically noticeable medium is absent. These conditions permit us to treat the motion of the stars by applying the well-known Newtonian equations of celestial mechanics. The solution of these equations leads to certain trajectories which the bodies follow in their motion through space. The distribution of masses in the solar system is such that Keplerian orbits (i.e., the conical sections: circle, ellipse, parabola, hyperbola, and the straight line) result in a high degree of approximation.

In the absence of frictional and propelling force (rocket engine) the body moves under the influence of its own inertia and the resultant gravitational forces only. According to the principle of d'Alembert the forces of inertia and gravitation exactly eliminate each other. A body is without weight under these circumstances. These conditions are valid only in the emptiness of space. Since our problem concerns the border-area of space, namely, the atmosphere, we have to deal with the influence of the atmosphere upon the motion of the body.

It follows from this point of view that the weight of the body depends on the extent to which it is allowed to move along its celestial trajectory that would result from the gravitational field of forces. Any kind of support arising from lifting, frictional, or propelling forces lends weight to the body by destroying the equilibrium between the forces of gravitation and inertia. Consequently, in deriving the conditions of weight and weightlessness we have to discuss the nature of lifting and frictional forces, and the propelling forces of the rocket engine.

Let δ_a be the air's density, v the velocity of the craft, and A a suitable area of reference (for instance, cross-section of the exhaust) then any aerodynamical force F can be described by

$$F=\delta_a.v^2.A.k \tag{1}$$

wherein Σk represents the sum of all spective force. The vectorial sum of all aerodynamical forces may be written as:

$$\Sigma F=\delta_a.v^2.A.\Sigma k \tag{2}$$

wherein Σk represents the sum of all coefficients. It may be noted that Σk does not vanish; Σk becomes meaningless if δ_a or v becomes equal to zero. The thrust of a rocket engine can be expressed by

$$T=\delta_g.c^2.A \tag{3}$$

wherein δ_g is the density of the exhaust gases, c the exhaust velocity and A the cross-section of the exhaust. The acceleration resulting from the lifting, frictional, and propelling forces can be written as

$$a_F+a_T=a=\frac{\Sigma F+T}{m}=[\delta_a.v^2.\Sigma k+\delta_g.c^2].\frac{A}{m} \tag{4}$$

in which m is the mass of the rocket.

Equation 4 can be multiplied by the fraction l/l, l being a linear element, and we arrive at

$$a_F+a_T=a=\frac{\delta_a}{\delta_b}.\frac{v^2}{l}.\Sigma k+\frac{\delta_g}{\delta_b}.\frac{c^2}{l} \tag{5}$$

in which δ_b represents $\frac{m}{A.l}$. δ_b is a measure of the specific density of the rocket.

If a in equation 5 assumes the value g (981 cm/sec²) the conditions

inside the craft are those of normal gravity.

In a rocket aircraft, for instance, which flies at a constant velocity parallel to the ground, the various factors in the right side of equation 5 are such that a becomes equal to g. However, as a in equation 5 vanishes, the gravity free state will result.

A detailed analysis of the interrelation of the various factors involved shows that gravity or the lack of gravity can be realized by a number of combinations of the different variables. These combinations represent a certain functional set of conditions causing distinct values of gravity including zero.

Equation 5 consists of two summands a_T and a_F. The possible values a_T and a_F can assume, are illustrated in the following scheme:

	$a_F=o$	$a_F\neq o$
$a_T=o$	I	II
$a_T\neq o$	III	IV

As indicated by this scheme, there are four different combinations of a_T and a_F which represents three characteristic categories.

$a=o$; zero gravity	I
$a\neq o$ gravity	II, III
$a\neq o$; gravity; or, in the special case $a_T=-a_F$ $a=o$; zero gravity	IV

I. Zero gravity.

$a_T=o$
$a_F=o$

These conditions prevail if:

1. $c=o$, and $\delta_a=o$, or
2. $c=o$ and, $v=o$

   1 is the case of a craft coasting outside the atmosphere.

   2 is the case of a body falling freely at the very beginning of its motion. It may be noted that, simultaneously, δ_a may have any value. Obviously a parachutist jumping from a balloon belongs to this case for an infinitesimal time.

II. Gravity

$a_T=o$
$a_F\neq o$

These conditions prevail if:

$c=o$ and, $\delta_a\neq o$; $v\neq o$

This case represents a rocket craft coasting within the atmosphere. Lifting and frictional forces provide weight.

III. Gravity

$a_T\neq o$
$a_F\neq o$

These conditions prevail if:

1. $c\neq o$ and, $v=o$; $\delta_a\neq o$
2. $c\neq o$ and, $\delta_a=o$; $v\neq o$

   1. is the case of a rocket craft at the moment of take-off.
   2. is the case of a rocket craft outside the atmosphere with operating engine cruising at any desired speed.

IV. Gravity; zero gravity.

$a_T\neq o$
$a_F\neq o$

1. Gravity prevails under these conditions, since we are dealing with the case of normal propelled flight within the atmosphere.
2. The condition of zero gravity can be realized under the special condition that $a_F= -a_T$. Speaking in terms of physics it means that the propelling forces balance the lifting and frictional forces. It follows automatically from these conditions that the craft is forced to describe a celestial trajectory inside the atmosphere. It may be noted that this case is the only practicable possibility of maintaining the zero-gravity state for some length of time within the atmosphere.[13]

It may be noted, that the density δ_b of the body is of some significance, if it assumes extreme values. The gravity of a body of great density will be less as compared to a body of small density under the same conditions.

From the foregoing it becomes evident that the phenomena of weight and weightlessness are not principally topographical in nature. As was shown in Case III-2, the engines of a craft can provide weight anywhere in space. On the other hand, as shown in Case I-2, and IV-2, gravity can be conditionally removed within the atmosphere of a planet. Naturally, the durations of the gravity free state as represented by Case IV-2, are limited, since the velocity of a body moving along in a celestial trajectory are such that the condition a_T—a_F cannot be maintained technically for more than 30 to 45 seconds.[13]

At high altitudes, however, the density of the air decreases. Consequently the condition of Case IV-2, can be maintained for longer periods of time and finally Case I-1 is realized if δ_a approaches zero. Owing to the decreasing support of the atmosphere with increasing altitude the borders of space from the viewpoint of weight and weightlessness are not sharply defined.

* * *

From what has been said in the foregoing we have indeed to conclude that an appraisal of the technical and medical problems of space flight from strictly topographical viewpoints is misleading.

In contrast to this, a functional interpretation reveals that at relatively low altitudes we will encounter or can produce conditions typical of space.

In view of this concept, space flight ceases to be a premature topic. For limited periods of time, manned rocket crafts of today are capable of cruising at heights where the various attributes of space are approximated to a very high degree. Space flight, as we have it today, differs in only one point from space travel in its usual, commonly accepted, meaning: at the present time it is still limited to durations of the order of minutes.

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FLIGHT AT THE BORDERS OF SPACE

by

Heinz Haber

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AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

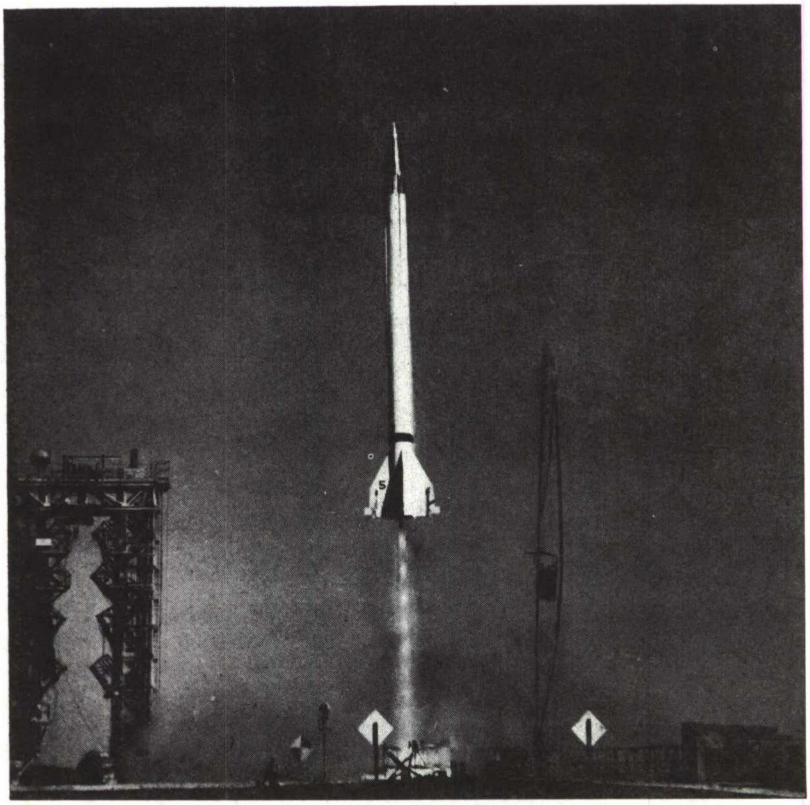
Flight at the Borders of Space

As aircraft and missiles attain higher and higher altitudes the question arises: Where, for practical purposes, does the atmosphere of the Earth end and interplanetary space begin?

by Heinz Haber

MAN'S CONQUEST of space will not be a single, crossing-the-Rubicon event. Long before the first Earth-dweller makes a landfall on the Moon, there will be other firsts. Many of these milestones have already been passed, and in a sense man is even now probing across the borders of space. In a recent experimental flight the Douglas Skyrocket, a pilot-carrying craft with a rocket motor, rose to an altitude where more than 96 per cent of the Earth's atmosphere lay below the pilot's feet. An unmanned two-stage rocket has climbed to 250 miles above the Earth's surface—at which height air molecules are rarer than in the best man-made vacuum.

To be sure, even at an altitude of 250 miles the missile had not yet passed entirely beyond the boundaries of this planet's atmosphere. At that height and even higher there are still enough air molecules to produce auroras. Moreover, no man-made rocket has yet achieved more than one third of the speed (about five miles per second) necessary to permit it to circle our planet permanently as an artificial satellite. Nevertheless, at an altitude of 250 miles the Earth's atmosphere for all practical purposes no longer exists, so far as effects on the rocket are concerned. For a few minutes at the top of its flight the unmanned 250-mile rocket was a true spaceship.



MARTIN VIKING rocket ascends from White Sands Proving Ground near Las Cruces, N. M. A rocket of this type has attained an altitude of 137 miles, a record for single-stage missiles. A two-stage rocket has risen 250 miles.

The boundary of the upper atmosphere is difficult to define. The frontier is commonly considered to be at about 600 miles, the limit at which the aurora borealis, the highest atmospheric phenomenon, is observed. But this definition has no significance for rocket flight or aviation. For fliers and rockets the critical boundaries are the levels at which the air becomes too thin for breathing, for filtering out cosmic radiations, for a balanced heat exchange or for affording a plane mechanical support. These borders come at different heights, and we have already passed several of them. In other words, our manned ships and guided missiles are already being exposed to some rigors that will not grow any worse no matter how much farther we go. Thus the conquest of space has truly begun.

Naturally most of the data on the performances of the newest rocket craft and planes must remain secret for reasons of national security. The problems of high-altitude flight are, however, accessible to public discussion.

THE U. S. Air Force requires crew members to use their oxygen equipment as soon as they reach an altitude of 8,000 to 10,000 feet. This furnishes a considerable safety margin, for nobody

will collapse from lack of oxygen below 20,000 feet. At about 10,000 to 12,000 feet, however, people begin to show symptoms of altitude sickness. For example, a person who walks around or takes any mild exercise at the 13,000-foot-high saddle point of Independence Pass, near the town of Aspen on Colorado State Highway 82, soon finds himself short of breath and may even become dizzy. By gradual acclimatization over periods of months or years people may adapt themselves to live at altitudes as high as 25,000 to 28,000 feet, as explorers training to climb the Himalayas have done. But a pilot suddenly exposed to the rarefied air at 25,000 feet will lose consciousness within three or four minutes. This is the so-called "time of useful consciousness" that a flier has for taking action to save his life, by dropping to a lower altitude or restoring the oxygen pressure in some other way.

As we go higher, the time of useful consciousness becomes shorter and shorter. At 30,000 feet it is only one minute, and at 50,000 feet it dwindles to 11 to 18 seconds. Beyond that height, however, it apparently does not decrease further. In experiments in the low-pressure chamber the time of useful consciousness levels off and stays at an average of 15 seconds up to a simulated altitude of 55,000 feet. There is no reason to believe that the time span would be shorter at higher altitudes; indeed, a theoretical analysis shows that 50,000 feet should be the critical altitude. The reasoning is as follows: At any altitude the air in the lungs has a different composition from that of the atmosphere outside the body. In the atmospheric air at sea level, where the total pressure is 760 millimeters of mercury, nitrogen accounts for about 580 millimeters of the pressure, oxygen for 150 mm., water vapor for 23 mm. and argon for 7 mm., while the proportion of carbon dioxide is negligible. In the lungs, on the other hand, the proportions are: 570 mm. of nitrogen, 106 mm. of oxygen, 47 mm. of water vapor, 40 mm. of carbon dioxide and 7 mm. of argon. The extra carbon dioxide and water vapor in the lungs comes from the blood by evaporation. Now as we go up to higher altitudes, the partial pressures of the gases in the air drop off; in other words, we have less and less oxygen and nitrogen to breathe. But the water vapor and carbon dioxide in our lungs stays practically constant at about 80 to 87 mm. of pressure. Obviously when we reach an altitude where this pressure is greater than the total pressure of the outside air, the capacity of our lungs will be claimed exclusively by the water vapor and carbon dioxide streaming profusely from our blood, and the lungs will be unable to take in any oxygen at all. The body must then live on the oxygen previously stored in the

DOUGLAS SKYROCKET, a rocket-powered aircraft, has been reported to have reached an altitude of 15 miles. It was borne aloft from Edwards Air Force Base near Muroc, Calif., by a B-29 bomber and launched in the air.

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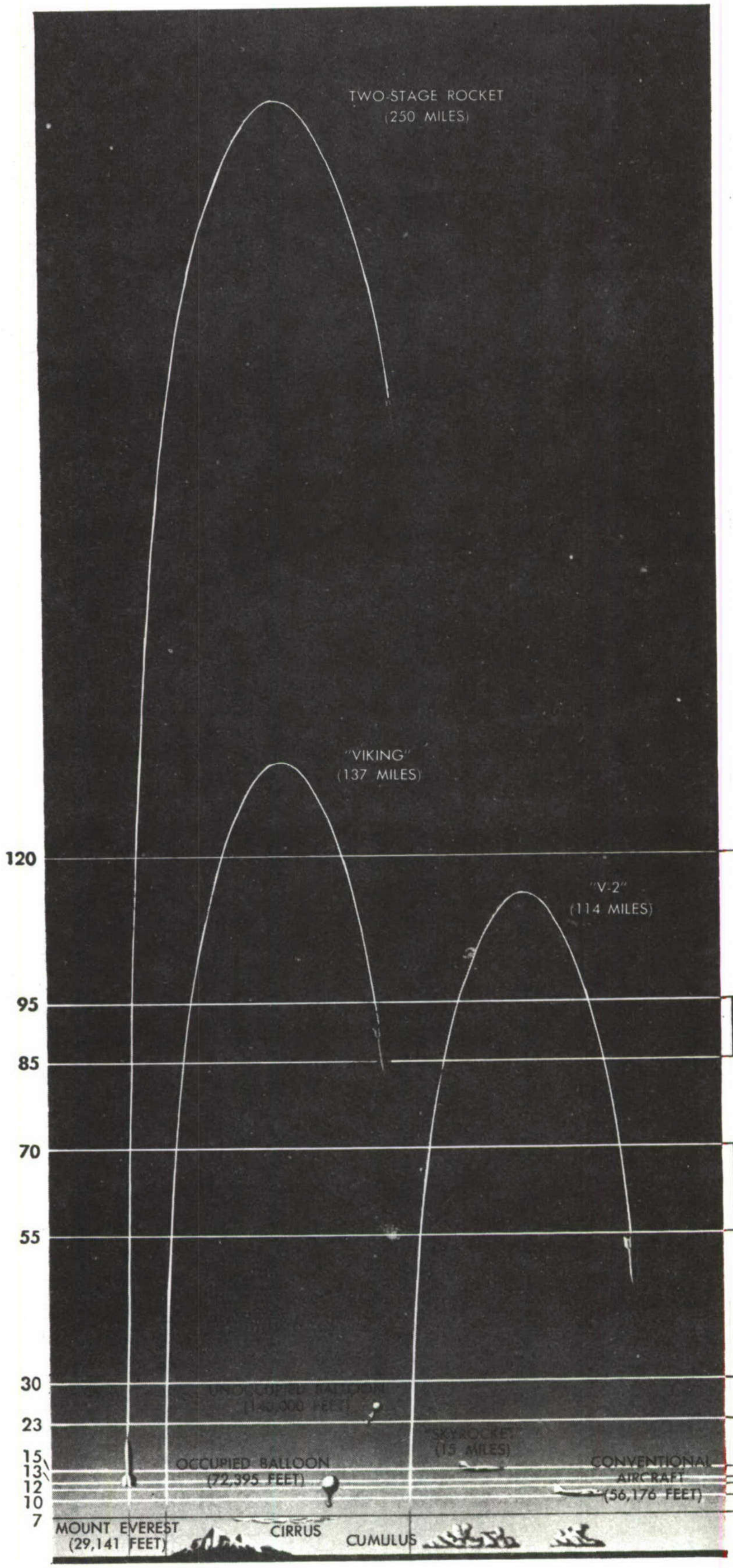
blood and tissues. It takes only about 15 seconds for the oxygen stored in the brain tissues to fall to a level that produces loss of consciousness.

The critical altitude (where the total air pressure drops to 80 to 87 mm.) is roughly 50,000 feet. This is the boundary at which the atmosphere's ability to make any contribution to man's respiratory needs comes to an end. In other words, so far as his oxygen supply is concerned man crosses the borders of space at an altitude of about 10 miles. Above this level he is on his own. The pilot of the Douglas Skyrocket crossed this border. In order to do so he had to be encased in an airtight envelope inside his cabin—*i.e.*, he wore a spacesuit.

NOT FAR above this border we come to a boundary where the oxygen becomes too thin to support even combustion. Here we must abandon terrestrial power plants such as reciprocating or jet engines and turn to rocket motors that carry their own oxygen. This critical frontier is somewhere around 70,000 feet. It, too, has been pierced by our rocket craft.

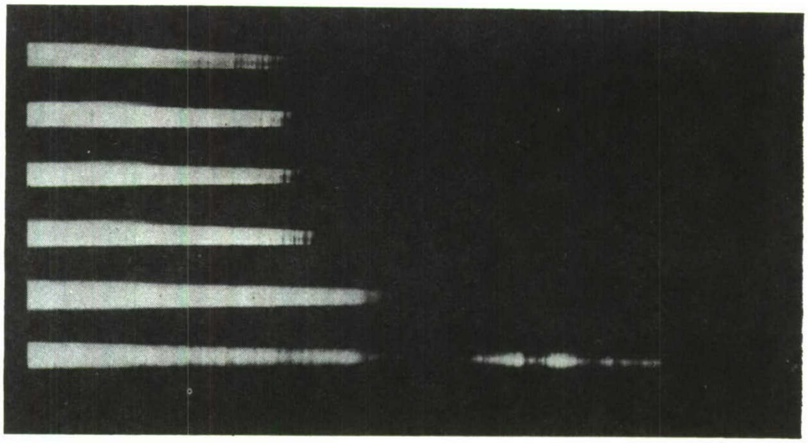
Just a little higher we begin to approach the ceiling of our protection against the hazardous ultraviolet radiation and cosmic rays. The atmospheric



BORDERS OF SPACE differ for various problems of high-altitude flight, some of which are listed below. The scale at the left is in miles.

blanket that shelters us thins out fast, and above about 90,000 feet the damaging ultraviolet rays are about 10 times as strong as at sea level. This kind of radiation can easily be warded off by the walls of a spaceship, but the more energetic primary cosmic rays are another matter. At 120,000 feet and above we approach the region where only the shadow of our planet and the planet's deflecting magnetic field can shield us from the cosmic particles.

A good bit above this—say at 300,000 feet, or 60 miles—we start to run into peril from meteors. Of the vast number of meteors that hit the Earth's atmosphere every day, few reach the ground, as most of them are burned up in the atmospheric region between 60 and 90 miles up. Above 90 miles we would run the same risk of being hit by meteors as in interplanetary space, except for the protection afforded by the shielding bulk of the Earth.



SPECTRA OF THE SUN made from an ascending V-2 rocket demonstrate how the intensity of the shorter ultraviolet radiation increases with altitude. The spectra, from top to bottom, were made at altitudes of 1, 4, 10, 15, 20 and 35 miles. The longer wavelengths are at the left; the shorter, at right.

At this altitude we shall also need artificial light in our spaceship, for the blue of the sky will have given way to the blackness of space. On the Earth the scattering of sunlight by the atmosphere gives us a soft, diffuse illumination. Above 90 miles the sky is as dark as the star-strewn heavens on a moonless night on Earth. Even at the altitudes already reached, pilots have trouble reading their instruments by day unless the panel is illuminated. The strong contrasts between the dark sky and a sunlit part of the airplane's structure are approaching the limit of discomfort.

The levels at which the atmosphere ceases to give mechanical support and heat exchange between the air and the ship ends will depend on the speed of the craft. Our high-speed aircraft already are becoming uncomfortably hot in flight. A fast-flying aircraft acts like a piston, compressing and heating the air in front of the nose and the leading edge of the wings. Friction of the air along the fuselage and the surface of the airfoil also produces heat, creating a thin film of hot air. A rocket pushed through the air at a speed four to five times faster than that of sound is enveloped in a film of air heated to more than 2,000 degrees Fahrenheit. Even at the supersonic speeds at which some of our jet aircraft fly today, cooling systems are needed.

The temperatures produced by compression and friction are independent of the density of the air. In the thin strata of the upper atmosphere a craft will still be enveloped in a film of hot air. But with increasing altitude the heat content of the envelope will decrease, and there will be less transfer of heat to the ship. Unfortunately we do not know precisely how fast a ship will be able to travel without becoming overheated, because the mechanism of heat transfer between hot envelope and craft is not well understood, especially in extremely rarefied air. We know that meteors are vaporized by air as thin as that found in the region between 60 and 90 miles of altitude. For a craft flying at five to six miles per second the thermal interaction between the atmosphere and the craft will become negligible only at an altitude of 110 to 120 miles. Above that height air compression and friction will cease to exist, and the temperature of the ship will be determined solely by the exchange of radiation between the outer hull, the Sun and the Earth.

HOW FAR an aircraft will be able to get lifting support from the air will depend on the ship's speed. The aerodynamic forces of lift and drag fall off in proportion to the air's density but increase in proportion to the square of the craft's velocity. It appears, therefore, that an aircraft could make up by velocity what the air lacks in density. There is, however, a limit. At very high speeds the lift-drag ratio becomes increasingly unfavorable, and the heating of the ship imposes insurmountable difficulties. Eventually, when the craft runs out of atmosphere, it will have to be supported solely by the thrust of its rocket engine; yet this device can only operate for brief periods of time.

Where the mechanical support of the atmosphere fails, the craft must rely on centrifugal force arising from a curved trajectory. If the ship is to take up a permanent orbit, its speed must be such that it stays on a closed trajectory in the shape of a circle or ellipse. In the absence of air drag, the forces of inertia then exactly balance the gravitational pull of the Earth. The vessel must not be slowed down by air drag. Loss of velocity would decrease the centrifugal force, and the radius of the ship's orbit would shrink at an increasing rate. It has been estimated that a ship circling the Earth at a distance of 80 miles in unpropelled flight would lose about six miles of altitude per revolution and would soon spiral down toward the Earth. At a height of 110 miles the altitude loss per revolution due to air drag would be only three feet. A few miles farther up the ship's orbit would be permanent, according to human time standards. At an altitude of 120 miles the aerodynamic forces vanish completely. For all practical purposes this level can be considered the mechanical border of space. Several unmanned missiles have risen to heights twice as great.

The disappearance of the frictional forces at highest altitudes is a matter of interest not only to the aerodynamics engineer but also to the passengers. Beyond the mechanical borders of the atmosphere the balance between the forces of gravitation and inertia would leave the crew weightless. The problem of weightlessness is already present in certain flight maneuvers, even within the atmosphere. In power dives and in parabolic flight maneuvers in which the aircraft is accelerated vertically downward at the rate of free fall a pilot may experience the state of weightlessness for 30 to 50 seconds. Consequently the phenomenon of weightlessness has no defined border.

Aviation based on jet and rocket propulsion is emerging into space flight by gradual stages, as our vehicles cross the borders of space and probe briefly into the realm beyond the thin atmospheric skin of this planet. Actually space flight today differs from space travel in its commonly accepted meaning in only one respect: our flights into space at the present time last only a few minutes.

Heinz Haber is a research scientist in the Department of Space Medicine of the Air Force School of Aviation Medicine.

ECOLOGICAL ASPECTS OF PLANETARY ATMOSPHERES WITH SPECIAL REFERENCE TO MARS

by

Hubertus Strughold

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Ecological Aspects of Planetary Atmospheres With Special Reference to Mars

By H. Strughold, M.D., Ph.D.

Department of Space Medicine, USAF School of Aviation Medicine Randolph Field, Texas

CURRENT KNOWLEDGE as to the composition of the planetary atmospheres is reviewed in *The Atmospheres of the Earth and Planets,* a book edited by P. Kuiper and published in 1947.[25] This comparative astronomical study indicates that only the atmospheres of Mars and perhaps Venus justify a comparative physiological and ecological study. Of special interest are the findings that CO_2 and H_2O are present in the Martian atmosphere and that the infra-red spectrum of the so-called green areas on Mars is compatible with the spectrum of lower plants (lichens and mosses).

The publication of the above-mentioned monograph certainly gives new impetus to the discussion of the possibility of life on other planets. It is inspiring for biologists to join such discussions originated by the astronomers: Schiaparelli, and especially P. Lowell[28] (see further, W. H. Pickering,[36] E. H. Mounder,[34] H. S. Jones,[21] G. T. Kuiper,[25] and G. deVaucouleur.[48]

Today physiological and ecological considerations to this end can be derived from a rather broad background of knowledge, since during the last few decades biology has made great progress in the study of the limits and stages of life as a function of environmental conditions.[10,37,38] In particular, cold and hypoxia have been the subject of intense research in aviation medicine.[4,5,7,15,27,35,41] On the basis of this present physiological experience we are able to exclude some manifestations of life and to consider others as possible on other planets.

This undertaking presupposes the assumption that the laws of biological processes are the same throughout the universe, and that the structure of living matter is based on the carbon atom and its unique chemical properties. Certain other assumptions — taking silicon to be the base atom, for instance—would trespass the bounds of sound speculation.

In this study we shall confine ourselves to the manifestations of life as we know them, and to apply to the physical environment on other planets, the yardsticks of physiology and ecology as they are valid on earth.[2] In doing so we can estimate the extent to which life on other planets is possible. At the same time we arrive at a better understanding of the limitations and abundance of life on our own planet.

In addition to being of general scientific and human interest, this subject is of special interest to aviation medicine and space medicine, two fields of study vitally concerned with the question of life under very extreme environmental conditions. No

planet offers a better stage for such physiological and ecological considerations than does the planet Mars. In this respect it is interesting to note that the Martian surface atmosphere has some properties in common with the terrestrial atmosphere at an altitude of about 10 miles.

According to common usage in terrestrial ecology, we shall study the question concerning life on planets from the viewpoint of the "law of the minimum" (J. von Liebig[26]) and the "principle of limiting factors" as has been elaborated by F. F. Blackman.[8] In their simplest form these laws state that the environmental factors—such as temperature, light, water, and chemical components of soil and air—impose limits to life by being either excessively strong and abundant or too weak and sparse. A certain minimum must be reached and a certain maximum must not be exceeded; only within these limits can life exist and develop. Between these two cardinal points lies a third one, representing the optimum of an environmental condition or of a combination of such conditions, which is distinguished by being particularly favorable for the flourishing of life. Although these cardinal points, as was found later,[8] are fluctuating greatly in relation to each other ("relatively limiting factors"), in the following study these principles will be applied in their simplest form to the planets and especially to Mars. We shall confine ourselves to two environmental factors, namely, temperature and oxygen.*

*A study including all environmental factors (Radiation, H_2O, CO_2, O_3 and some unusual constituents of planetary atmosphere such as NH_3, CH_4) will be published soon.

OVERALL ECOLOGICAL VIEW OF THE PLANETS FROM THE STANDPOINT OF TEMPERATURE

Active processes of life such as growth, metabolism, activity, reproduction, etc., take place only within

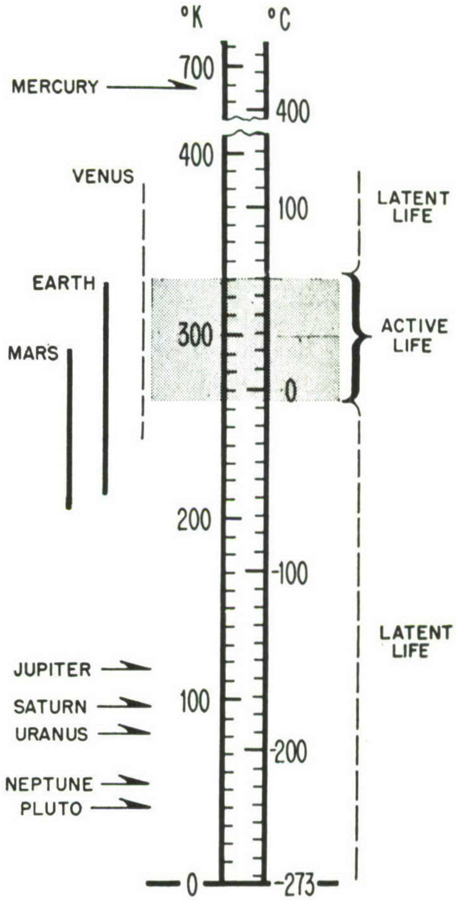

Fig. 1. *(Left Side)* Surface temperature of the planets. *(Right Side)* Temperature scale of life.

a temperature range (prevailing in the tissue) between a few degrees below the freezing point of water and about +55° to 60° C. (Fig. 1). Above this temperature living matter is transposed into the state of "heat rigor"

and soon perishes (dehydration, enzyme inactivation, protein coagulation). Only the thermophilic bacteria are still capable of growing at temperatures up to 75° C. Spores of bacteria and certain seeds can survive if exposed to temperatures of +120° C. for several hours. Below the minimum temperature required for active life lies the beginning of the lethal range for most organisms; yet, as is known, arctic plants survive temperatures down to —60° C. Thus it was found experimentally, by immersing the specimens in liquid nitrogen, oxygen, hydrogen, and even helium, that certain lower organisms such as algae, bacteria, lichens, and mosses are capable, for weeks, of withstanding temperatures closely approaching absolute zero. The living matter is hereby transposed into the state of "cold rigor" which also can be designated as the state of latent or dormant life. Summarizing, we can state that there is no decrease of temperature capable of destroying, unconditionally, every form of living matter, provided the onset of cold follows certain temporal patterns.[16,18,23]

If we now consider the temperatures found on the surface and in the atmospheres of the planets,[43] we see that Mercury's temperature lies far above the maximum cardinal point, within the lethal range (Fig. 1). Venus with more than 100° C. in its lower atmospheric layers and about —25° C. in its outermost stratum approaches biological temperatures only in certain higher strata. The temperatures found on earth ranging from —60° to +50° C. cover the entire range of active life with its upper half, while they also cover about 60 centigrades of the cold range of latent life. The Martian temperature range with its upper quarter coincides with the lower part of the biothermal band and covers more than 60 centigrades of the cold range of latent life. The larger planets lie deep in the temperature range of latent life, in other words 150 to 200 centigrades below the temperature minimum for active life.

It may be added that the temperature of the moon varies between —150° and 100° C.

In conclusion the following may be said: From the standpoint of temperature, Mars and possibly Venus* are the only planets, aside from the Earth, which at present possess the prerequisites of life, in our sense. In this connection, it must be considered that in view of the large diurnal amplitudes of temperatures only eurythermal liv-

*In regard to Venus, H. Haber (personal communication) presumes that life in the form of a biological aerosol may exist in certain strata of the Venusian atmosphere, where the temperature conditions for the existence of life are fulfilled. Haber further thinks it possible that life attempts to gain a first foothold on planets within their atmospheres in the form of these biological aerosols. There, life becomes a major factor in the development of the chemical constitution of planetary atmospheres. As a consequence, the living matter alters gradually its chemical and thermal environment by changing the atmosphere's constitution, its absorptive qualities regarding solar energy, and its proper radiation, until life may finally succeed in developing explosively. According to this concept, life does not depend entirely on the chances of the creation of a suitable environment effected through inorganic processes on the surface and within the atmosphere of a planet; instead, life itself invades a planet and attempts to form an environment favorable for extensive development. In the light of this concept, Venus and Earth can be considered as presently being in different stages of development.

ing beings can exist on Mars, i.e., those which can resist changes of temperature within a wide range. This physiological requirement also points toward certain lower organisms, such as algae, lichens, and mosses, which are characterized by pronounced eurythermia.

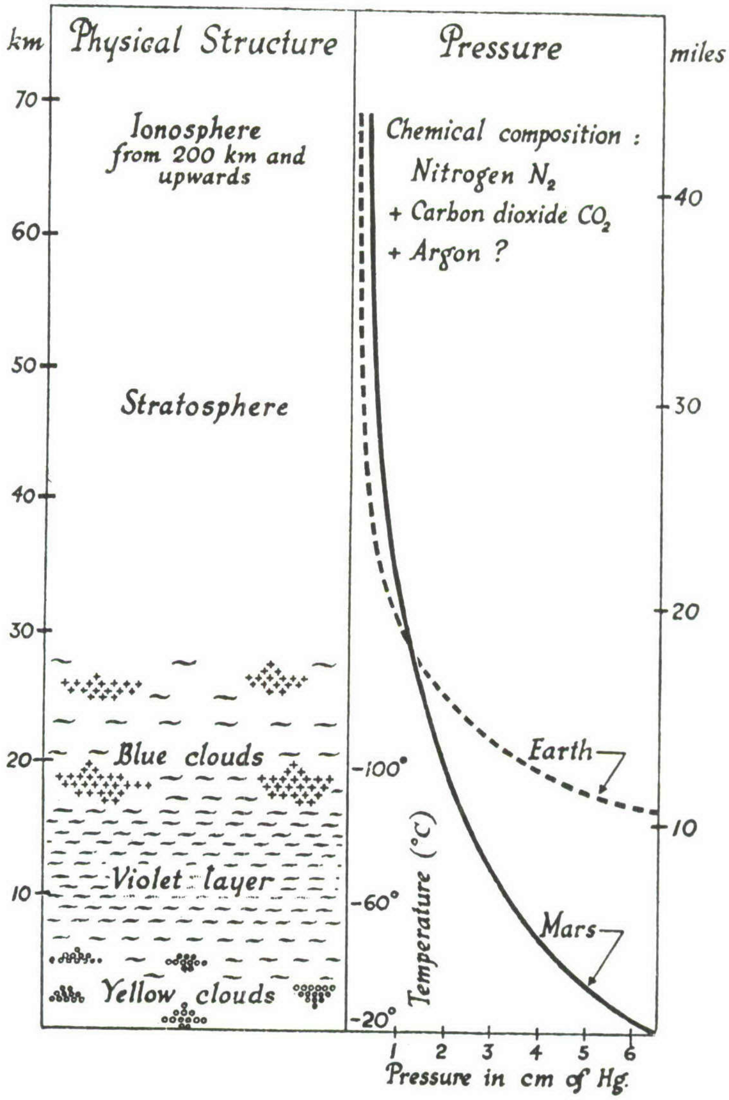

Fig. 2. Summary of the present state of knowledge concerning the atmosphere of Mars. (After G. de Vaucouleurs, The Planet Mars. London: Faber and Faber, Ltd., 1950).

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POSSIBILITY OF LIFE ON MARS AND THE PROBLEM OF OXYGEN

Mars might actually be considered a biophilic planet, in regard to temperature, but its combination of ecological

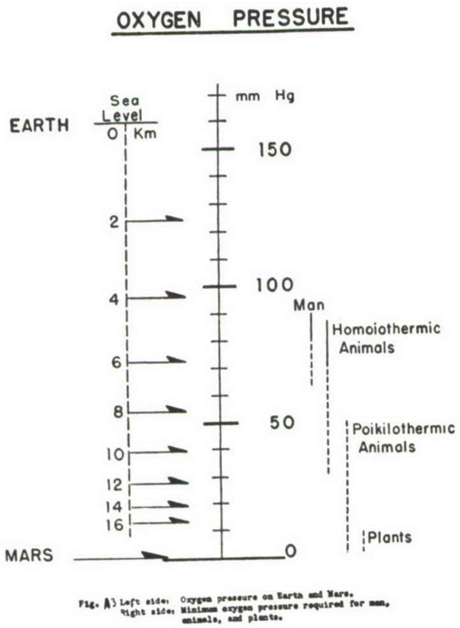

Fig. 3. *(Left side)* Oxygen pressure on Earth and Mars. *(Right side)* Minimum oxygen pressure required for man, animals, and plants.

conditions† (Fig. 2)[43,50] shows a very weak point: Oxygen cannot be found in the Martian atmosphere.[1,25]

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†Physiologically Important Astronomical Data of Mars

Period of Rotation	: 24 Hrs. 37 Min. 23 Sec.
Period of Revolution	: 780 days
Acceleration of Gravity	: 0.37 g
Solar Constant	: 0.84 g cal/cm^2 minute
Temperature Range	: -60 to+30° C.
Atmospheric Pressure	: 60 to 80 millibar
Oxygen Pressure	: Below 0.5 millibar, if any
Carbon Dioxide Pressure	: Equal or even exceeding the terrestrial value.

Oxygen, apart from carbon, is the bioelement par excellence because (1) on the average, oxygen makes up 60 per cent of the living matter (water included); and (2) the most important energy source of the organisms is biological oxidation (aerobic respiration). Another source of energy, though less significant, is anaerobic respiration which requires no oxygen. However, the substances undergoing anaerobic respiration consist of oxygen, to a rather large part.

THE VITAL OXYGEN MINIMUM

The production of energy which is based on biological oxidation consumes large amounts of oxygen and requires a certain concentration of oxygen in the medium surrounding the organisms. For man, for instance, this concentration must be of the order of 5.5×10^{18} oxygen molecules per cm.^{3} of air. Physiologically, this concentration or the corresponding pressure is likewise limited by a maximum and a minimum; exceeding these limits is incompatible with life. In the following we are mainly interested in the oxygen minimum which is just sufficient to permit a "vita minima."

For man the minimum oxygen pressure is about 65 mm. Hg (corresponding to an altitude of 7,000 m.) (see Fig. 3). Acclimatization to altitudes of about 7,000 m. is possible for some time, as shown by experiments in low pressure chambers and various Himalayan expeditions,[3,4,7,8,9,13,16,17,29,41] but permanent settlements are found up to 5,000 m. only (Andes). Thus, we can conclude that the presence of manlike creatures on Mars belongs to the realm of fantasy, since the minimum

oxygen pressure required for man is at the least 100 times larger than the O_2-pressure which may at best be present on Mars.

It was found in decompression chamber experiments that the vital minimum oxygen pressure of homoiothermic animals (monkeys, dogs, cats, rabbits, guinea pigs, rats, pigeons) corresponds to an altitude of 8,000 to 12,000 m., i.e., barely less than 50 mm. Hg (Fig. 3). Poikilothermic animals (reptiles, amphibians, fishes, worms, etc.) withstood pressures below 50 mm. Hg down to 5 mm. Hg and less.[9,12,32] We know that a number of animals of the lowest species can live without oxygen for quite some time, e.g., in deep layers of stagnant lakes.[22,37,38] Oxygen-free habitats are likely to develop in ice-covered ponds and lakes, if there is a high oxygen consumption by organisms. It is necessary that systematic investigations on the oxygen-pressure demand of poikilothermic animals be performed, since many of the experiments and observations made so far are only informative. Be that as it may, so far as the animal kingdom is concerned, the presence of homoiothermic and higher poikilothermic animals on Mars must be negated in view of the prevailing oxygen pressure. Arguing about the presence of lower species is futile because of the lack of clues to justify such argumentation.

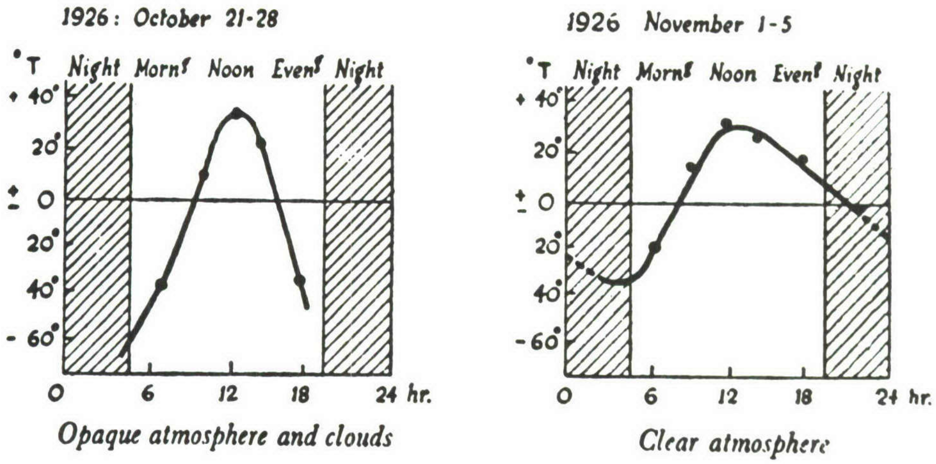

Fig. 4. Diurnal temperature variations in the southern tropical regions of Mars near midsummer of the southern hemisphere, according to the radiometric measurements of W. W. Coblentz at the Lowell Observatory in 1926. (From G. de Vaucouleurs, The Planet Mars. London: Faber and Faber, Ltd., 1950).

There are clues, however—namely, visible ones—that suggest the possible existence of vegetation on Mars. These clues are the seasonal discolorations of the green Martian areas (Lowell[28]) and the spectroscopic finding made by Kuiper.[25] Accepting this vegetation hypothesis,[28,36] we are confronted with the problem of how to view it from the standpoint of physiology, since we must consider the ap-

parent lack of oxygen in the Martian atmosphere.

It is true that plants also respire and require oxygen, though they are able to switch to anaerobic respiration at any time.[24] There are plants which stop respiration as soon as the oxygen pressure of the air falls below 1.5 mm. Hg. This point is designated as the physiological zero point of plant respiration.[20,40] For growth and development, plants generally need a higher oxygen pressure. Notwithstanding, plants can overcome this difficulty by their ability to produce oxygen through the process of photosynthesis; in this respect, plants are superior to animals. They have their own oxygen generators in the chlorophyll-containing chloroplasts.[30,42] As is well known, photosynthesis requires carbon dioxide and water as raw materials, as well as light and a certain temperature.[33] Do these factors reach or exceed the physiological minimum for the process of photosynthesis on Mars?

First of all, the temperature minimum for photosynthesis lies generally some degrees around the freezing point of water. Yet, in some arctic plants (lichens) a minimum of –20° C. has been observed. During daytime on Mars, these temperatures are exceeded by 20 to 40°.[11] (Fig. 4).

Second, the minimum of light is certainly exceeded, since the solar constant on Mars averages 0.84 g cal/cm.^{2} min. (40 per cent of the terrestrial solar constant).

Third, the amount of carbon dioxide in the Martian atmosphere is, according to Kuiper, higher than that found in the terrestrial atmosphere.

Fourth, the presence of H_2O on Mars can be taken for granted. Still, the water question is possibly the weakest point in the combination of conditions for photosynthesis on Mars.

In short, if this last factor should not be definitely below the minimum (see J. Franck[14]), photosynthesis (as we know it) should be possible on Mars, since all other factors are adequate. Moreover, the combination of conditions for photosynthesis on Mars is, on the average, farther away from the optimum than is that on Earth. It is, therefore, improbable, that plants of higher order—such as vascular plants—can exist on Mars because of their higher demands as to temperature and humidity. Only lower plants which are very cold-resistant and drought-enduring (xerophytes) would be able to stand up against such climatic conditions. Kuiper's spectroscopic observations suggest the presence of lichens and mosses.[25] Lichens and mosses belong to the two lowest subdivisions in the plant kingdom, the thallophytes and bryophytes. The lichens have some very peculiar characteristics (see monographs[44,46]). They consist of two dissimilar organisms, a fungus and a number of algae (conidia), living in symbiosis. The fungal component offers protection from cold and supplies inorganic substances including water (because of the hygroscopic nature of most fungi). The algal component builds up organic substances and supplies oxygen through photosynthesis. On account of this ideal symbiosis, lichens are very resistant to a dry and cold environment; they have hardly any demands as to the substratum upon which they live. We find them growing on barks of

trees, and even on the surface of rocks and monuments. In the subarctic zones they represent the chief vegetation (reindeer "moss"). In the Himalayan mountains they can be found at altitudes up to 5,000 m. In short, they are the "last outposts" of plant life in every direction. They can exist on bare rocks because of their ability to decompose rock by producing organic acids. In this way they are "pioneer plants," preparing the humus for more demanding plants.[16] In the course of the Earth's history they may well have made the first start for vegetation that developed on barren volcanic rocks. This phenomenon can be observed, for instance, on the lava masses of the Sunset Crater in Arizona.

Liverworts, the more primitive types of the bryophytes, are almost as resistant as the lichens.

In fact, from the biological point of view, it is tempting to assume—even if there is no oxygen as on Mars, for instance—that plants similar to lichens and mosses may also be the last outpost of life and the pioneer plants on other planets.

INTERNAL ATMOSPHERE

Terrestrial plants have developed a mechanism which aids in the process of respiration, transpiration and photosynthesis. This mechanism, when applied to an oxygen- and water-poor environment like that on Mars, affords a further support for the hypothesis of Martian vegetation. It is the phenomenon of the "internal atmosphere." As is well known, the microscopic picture of the thallus of lichens (Fig. 5) and liverworts and that of the leaves of higher plants show intercellular air spaces. Especially pronounced is this manifestation in the leaves of plants submerged in water. This system of intercellular air

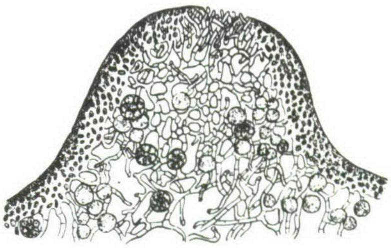

Fig. 5. Cross section through the thallus of a lichen; 175 times. (After Rosendahl, from Fr Tobler. Berlin: Verlag Borntraeger, 1925).

spaces is also called "aerenchyma." The maze of intercellular air passages is so widely spread that practically each cell of the parenchyma is in contact with the internal air. On account of this spongy structure, the inner surface of a leaf is much larger than the outer one. The ratio of inner to outer surface of leaves of different species ranges between 10 and 30.[47] The intercellular air spaces are in contact with the ambient air through pores or stomata. There are several hundreds of such pores per square millimeter of the upper or under leaf surface, respectively. Referring to lichens, some of these plants are equipped mainly with primitive openings called "cyphellae," (Fig. 5).

The physiological significance of this intercellular airing system is obvious. Not only is the area of exchange between leaf and environment increased enormously—a fact reminding us of the surface area of the pulmonary alveoli (= 100 square meters)

—there has also been created a kind of endoatmosphere, or *internal atmosphere*. It is this "private atmosphere," not the ambient air, with which the cells are in direct gas exchange. The microclimate with which the plants supply themselves is more apt to meet the requirements in regard to environmental conditions (for instance, water vapor and oxygen). Analyses of the intercellular air revealed that their oxygen content may amount to 30 to 60 volumes per cent.[33] Hence the air space serves to store the surplus oxygen produced by photosynthesis. In this way the system of intercellular air spaces facilitates the existence of plants in an oxygen-poor or oxygen-free environment (submerged water plants). Suppose the micromorphological structure of the hypothetical Martian plants had developed according to similar lines, then the objection that can be advanced against the existence of vegetation in an oxygen-free Martian atmosphere would lose weight. The picture of Martian plant life could be visioned as follows:

Active plant life on Mars could be possible only on that side of the planet exposed to sunlight, as soon as—after sunrise—the combination of environmental conditions within the internal atmosphere becomes adequate. After sunset the plants would return to a dormant state. Plant life would then be photorhythmic—without light, no active life.

Perhaps, during the Proterozoic era on Earth, the first primitive life was intermittent in a similar way. Today, the terrestrial plants have an oxygen reservoir of $1.2 \cdot 10^{21}$ g within the atmosphere, so they can continue breathing during the night. However, plants existing in an oxygen-free atmosphere, such as on Mars, are forced to live on the "current production" of oxygen. They consume the oxygen in "statu nascendi," or take it from the small stores of their microclimate. After sundown, the plants return to a state of latent life on account of the cold. In an oxygen-poor or oxygen-free milieu, the combination of dark plus cold seems to be more adequate from the physiological viewpoint than darkness plus higher temperatures. In the latter case plants can develop, in general, only if the ambient atmosphere—like that on the Earth — contains oxygen in amounts sufficient for respiration at night. Vegetation on Mars absolutely requires cold nights in view of the hypoxia—or better even, anoxia—existing on this planet.

From the physiological standpoint, therefore, the assumption of a Martian vegetation does not create insurmountable difficulties. This is particularly so if due consideration is given to the relativity of the physiological combination of environmental factors, as well as to morphological and functional adjustments of the living organisms to extreme environmental conditions, as are found in great variety in terrestrial biology. When considering these facts, the oxygen problem offers fewer difficulties than is frequently assumed. It is not oxygen, but carbon dioxide, that is the "conditio sine qua non" for vegetation.

The problem of the presence of oxygen in the Martian atmosphere might be formulated from the physiological point of view as follows:

Although according to the findings

in astronomy, Mars practically does not have any atmospheric oxygen, from the aspect of physiology there might be an oxygen layer within the vegetative substrate which, at adequate temperature and humidity, moves around the planet together with the sunlight.

In regard to Haber's hypothesis concerning the possibility of life in the Venusian atmosphere, the biological aerosol within the proper layers of the atmosphere of this planet also could benefit from a similar morphological structure that permits formation of an internal atmosphere by drawing oxygen from the ambient carbon dioxide through the process of photosynthesis.

In concluding this subject, I want to thank Dr. Heinz Haber for his advice in pertinent astronomical questions and for very informative discussions.

SUMMARY

The question of the possibility of life on other planets has been approached under the aspect of principles of physical and physiological ecology such as the principle of limiting factors, adaptive processes, et cetera. The discussion has been confined chiefly to temperature and oxygen as ecological factors.

Comparing the scale of bio-temperatures with the temperatures found on the surfaces and within the atmospheres of the planets we find that only Mars and, possibly, Venus are left as ecological spaces since their range of temperatures partially covers the "thermo-band of active life."

Further discussions concern the ecological properties of the Martian atmosphere emphasizing the oxygen question in terms of the minimum pressure of O_2 required for living beings. So far as plant life on Mars is concerned the minimum of environmental factors required for respiration and photosynthesis has been discussed at some length. Emphasis is given to the importance of certain manifestations of adaptation of the microscopical structure of plant tissue such as intercellular air spaces, which —providing an "internal atmosphere" —could considerably facilitate the existence of plant life within a milieu free of oxygen such as on Mars. The assumption of such adaptive morphoses to have taken place in the hypothetical Martian vegetation would diminish physiological objections that can be advanced against its existence.

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MANNED FLIGHT AT THE BORDERS OF SPACE. The Human Factor of Manned Rocket Flight

by

Heinz Haber

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

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The Human Factor of Manned Rocket Flight

HEINZ HABER[2]

Institute of Transportation and Traffic Engineering, University of California, Los Angeles, Calif.

A functional border between atmosphere and space is defined as a level at which the atmosphere fails as a supporting medium, and space-equivalent conditions begin. Depending upon a particular kind of function the corresponding limit is located at a certain altitude. The major functions of the atmosphere for man and craft are the following: Contributing to respiration, preventing boiling of body fluids, sustaining combustion of fuel, absorbing heavy primaries of cosmic radiation, absorbing solar UV-radiation, supplying aerodynamic lift, supplying diffuse daylight, absorbing meteors, interacting thermally with the craft, and interfering by air drag over long periods of time (permanence of satellite orbits). Depending upon the nature of a particular function, the functional borders so defined are more or less extended regions. The various functional borders of space lie in the region between 10 and 120 miles of altitude. The significance of the above mentioned factors for manned rocket flight is discussed with special emphasis upon problems of aero-medical and space-medical nature. The use of the term "aeropause" for the border region between atmosphere and space is proposed.

THE upper boundary of the atmosphere is commonly identified with that region of the exosphere where the upper most geophysical phenomena, namely the highest aurora, are occasionally observed. In terms of this concept, the limit of the terrestrial atmosphere is located at about 600 miles above the surface of the earth. The peak of the highest rocket trajectories attained so far—250 miles—lies yet within the boundaries of the atmosphere. For all practical purposes of rocket engineering, however, the atmosphere ceases to exist at an altitude of 110–120 miles. Unmanned rocket craft are routinely reaching beyond the physically effective regions of the atmosphere, and manned flights in the border region of the atmosphere are being made in experimental rocket airplanes. Flights at very high altitudes, i.e., in excess of 10 miles, are still short in duration; nevertheless, the technical means available in aviation of today make it necessary to investigate the medical and psychological problems peculiar to flight in the border area between the terrestrial atmosphere and space.

Since the geophysical concept of the borders of the atmosphere is of little use in aviation medicine and space medicine, a new concept must be found. This new concept must be adapted to the uses of rocketry and aviation medicine, in other words, it must be based on the functions which the atmosphere fulfills for craft and men. In a series of papers, Haber (1, 2)[3] and Strughold et al. (3) attempted to develop such a new concept by introducing the "functional borders between atmosphere and space." A functional border is defined as a certain level above the ground at which the atmosphere fails as a supporting medium. Depending on the nature of the various functions, the borders are located at different altitudes. They are found in the area between 10 and 120 miles of altitude. In these regions of the atmosphere the conditions of conventional aviation gradually blend into those of actual space flight.

From this point of view the following functional borders can be listed:

TABLE 1

	Function	Altitudes, miles
1	Contributing to respiration	10
2	Preventing boiling of body fluids	12
3	Sustaining combustion of fuel	13–15
4	Absorbing heavy primaries of cosmic radiation	13–23
5	Absorbing solar ultraviolet radiation between 210 and 300mμ (Hartley band of O_3)	22–28
6	Supplying aerodynamic lift	50–60
7	Supplying diffuse daylight	60–90
8	Absorbing meteors	65–95
9	Interacting thermally with the craft	100–115
10	Interfering by air drag over long periods of time (permanence of satellite orbit)	120

In addition to these data it may be mentioned that the presence of ozone above the 8-mile level can result in toxic concentrations of this gas in the cabin air, if the pressurization of the cabin is maintained by compressing ambient air. Fortunately, ozone is easily intercepted by means of simple filters.

Of course, the functional borders so defined are more or less extended regions. Especially the functions mentioned under 6, 9, and 10 are dependent upon the velocity of the craft, and the altitude data given are related to a velocity of the order of 5 miles/second. This velocity must be attained in order to establish a craft in a permanent satellite orbit around the planet.

In the following, those functions of the atmosphere that have a bearing on the human factor of manned rocket flight will be discussed briefly.

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[2] Associate Physicist.

[3] Numbers in parentheses refer to the Bibliography on page 276.

A The Function of Contributing to Respiration

Quantitative information as to the extent to which the atmosphere can maintain the oxygen supply of the body is obtained through experiments on explosive decompression. In experiments of this kind, a test subject is transposed, within fractions of a second, from an environment of normal or slightly reduced oxygen pressure to a state of acute oxygen need such as would be found at higher altitudes. If a subject is brought abruptly from normal oxygen pressure to that found at 5 miles the first psychophysiological disturbances can be observed after about two minutes; after another minute the subject becomes entirely helpless, and loses consciousness. The interval during which he is still capable of acting is called the "time of useful consciousness" after Armstrong (4), or "time reserve" after Strughold (5). This characteristic time span is reduced to about 80 seconds at 6 miles, and it is further reduced with increasing height, and finally reaches an asymptotic value of about 15 seconds at a height of 9 to 10 miles. Fig. 1 shows the time of useful

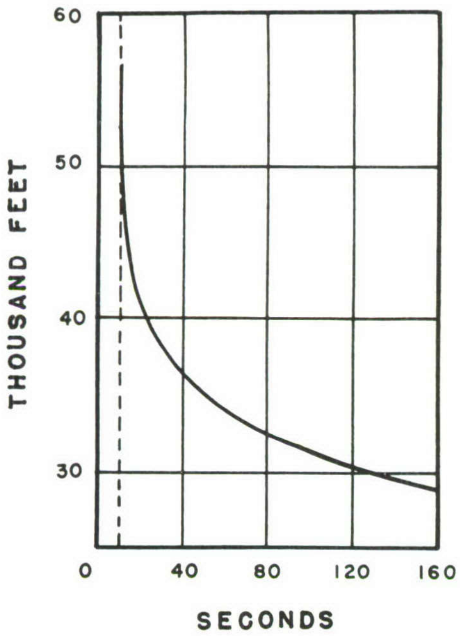


FIG. 1 TIME OF USEFUL CONSCIOUSNESS AT VARIOUS LEVELS OF ALTITUDE

consciousness as a function of altitude according to measurements carried out by Luft, Clamann, and Opitz (6). In experiments made in the low-pressure chamber at simulated altitudes up to 12 miles, the time of useful consciousness remained constant at an average of 15 seconds. There is no reason to assume that the minimum time span of 15 seconds will become any shorter at still greater heights. The height of the critical level in the atmosphere—about 10 miles where we first observe the minimum time reserve—can be derived from an analysis of the alveolar gases. The constitution of the air in the lungs differs from ambient air. In average atmospheric air of 760 mm Hg, about 580 mm are provided by N_2, 150 mm by O_2, 23 mm by water vapor, and 7 mm by A. The rare constituents of free air, such as the other inert gases and CO_2, are omitted in this listing. The approximate values for alveolar air at sea level are: 560 mm N_2, 106 mm O_2, 47 mm water vapor, 40 mm CO_2, and 7 mm A. At higher altitudes the partial pressures of the individual gases in free air fall off in exactly the same rate as the total pressure, since the atmosphere is being kept mixed thoroughly throughout. (The gravitational separation of atmospheric gases existing in the 22–30 miles layer and above, Ref. 7, can be omitted in this discussion.) Alveolar air, however, behaves differently. If air of a lowered total pressure is breathed, the partial pressures of nitrogen and oxygen in the lungs are likewise lowered proportionally; the partial pressures of water vapor and carbon dioxide, however, remain practically constant at about 80 to 87 mm Hg. This is because water vapor and carbon dioxide inside the lungs originate from the blood through continuous evaporation and exhalation. At increasing heights, water vapor and carbon dioxide occupy an ever-increasing percentage of the alveolar air. Obviously, the air inside the lungs will consist exclusively of these two components as soon as the pressure of the ambient air falls to 80 to 87 mm, a value which is reached at an altitude of about 9 to 10 miles. At this altitude no additional oxygen can enter the lungs because their capacity is exclusively claimed by water vapor and carbon dioxide. The function of the atmosphere to contribute to man's respiratory needs comes to an end at an altitude of about 10 miles.

B The Function of Preventing Boiling of Body Fluids

At a somewhat greater altitude the barometric pressure of the atmosphere can no longer prevent the body fluids from boiling. The boiling point of body fluids is reached at an altitude where the barometric pressure becomes equal to the water vapor pressure at body temperature, i.e., 47 mm Hg at 98.6 F. The critical level where boiling of body fluids sets in, lies at about 12 miles of altitude. Armstrong (8) has studied the boiling of body fluids in a low pressure chamber by exposing animals to a barometric pressure below 47 mm Hg. The first manifestations of boiling of body fluids appeared as rapid bubbling of the saliva around the mouths of the animals. After a delay of several seconds, ballooning of the animal skin was observed which is attributed to the formation of water vapor bubbles in the soft tissue. Boiling of blood in the lungs must also be expected upon lowering the barometric pressure below the critical value of 47 mm Hg.

C The Function of Absorbing Heavy Primaries of Cosmic Radiation

Originally, the cosmic ray particles were thought to consist exclusively of protons, i.e., the nuclei of hydrogen atoms. In 1948, Freier, Lofgren, Ney, and Oppenheimer (9) presented evidence to the fact that primary cosmic radiation contains also nuclei of heavier atoms. Bradt and Peters (10) determined the abundance ratio of different nuclear species in primary

cosmic radiation. Their results indicate that the following ratios exist: H:He:Heavier nuclei = 79:20:1. This frequency distribution can be expected to correspond approximately to the cosmic abundance of the chemical elements. Owing to the tremendous energy of the cosmic primaries ($\sim$ 2 BeV per nucleon), they are characterized by an enormous energy dissipation in passing through matter. This energy dissipation, which is dependent upon velocity and nuclear charge of the individual particles, determines the penetrating power of the particles. Consequently, the lower limits to which a certain percentage of the primaries can penetrate exhibit a certain stratification according to atomic number and energy of the particles.

About one half of the primary protons penetrate down to an altitude of approximately 12.5 miles. The lower limit of the heavy primaries is found at about 12 miles. Above this level their number increases considerably reaching a saturation at an altitude of about 23 miles. The air blanket above this latter level has no appreciable effect on the density and nature of the incoming particles of cosmic radiation.

Because cosmic rays are a highly ionizing type of radiation, their possible hazard to man exposed to them at greater altitudes must be investigated. The biological effectiveness of cosmic radiation was studied theoretically by Krebs (11), Schaefer (12, 13, 14), and Muller (15). Krebs gave special emphasis to the possible effects of the so-called star phenomenon. A primary particle entering the atmosphere from outer space carries such a high energy that specific hitherto unknown phenomena are produced in the processes of collision between a cosmic ray particle and a target nucleus. The cosmic ray particles create an explosion or "evaporation" of nuclei resulting in a complete disintegration of nuclei. The fragments shooting away from the site of the nuclear event imprint themselves on the emulsion of a photographic plate producing star-like formations. A typical star is shown in Fig. 2. According to Hornbostel and Salant (16), the frequency of stars with 4 or more prongs is about 2000 per cubic centimeter per day, at an altitude of 17 miles. Krebs estimates that the total of the prongs produced in the tissue of an individual exposed to cosmic radiation outside the air blanket is equivalent to a concentration of 6.2×10^{-12} grams radium elements per cubic centimeter. Comparing this figure with the natural occurrence of radioactive materials found in human tissue, Krebs concludes that "the radiation delivered by the cosmic ray stars at the top of the atmosphere comes very close to the amounts of radioactive energies which today are considered to be in no way harmless to tissue . . . the possibility for biological effects of cosmic radiation becomes, to a certain degree, reality."

Hermann J. Schaefer has evaluated the present-day knowledge of cosmic radiation in terms of the hazard to health. He was the first to point out that the heavy particles of cosmic radiation must be expected to be particularly effective, even though their number is small compared to that of primary protons. A detailed analysis by Dr. Schaefer of the biological aspects of the heavy primaries of cosmic radiation is given elsewhere in the JOURNAL (see pages 277–283 in this issue).

D The Function of Absorbing Ultraviolet Solar Radiation

The existence of ozone in the atmosphere in quantities sufficient to entirely block the passage of ultraviolet radiation from the sun was first assumed by Hartley (17), the discoverer of the absorption band of ozone between 210 and 300 mμ, that bears his name. The absorption of ozone begins at about 300 mμ, and soon becomes so effective that the solar spectrum is cut off abruptly at 286.3 mμ, as reported by Goetz (18). The maximum of ozone absorption lies at 255 mμ, where the absorption coefficient α_{10} was found to be as high as 123/cm. A layer of ozone at standard pressure and temperature, having a thickness of 0.002 cm, reduces the flux density of an incident beam of ultraviolet light to about one half. This shows that ozone is a more effective absorber than all metals.

The bulk of atmospheric ozone is found in the layer between 9 and 25 miles of altitude. The mean total amount of ozone corresponds to a layer of 3-mm thickness at STP. The existence of this small amount of ozone in the atmosphere is nevertheless of great biological importance. It provides an extremely effective blanket against those parts of ultraviolet radiation

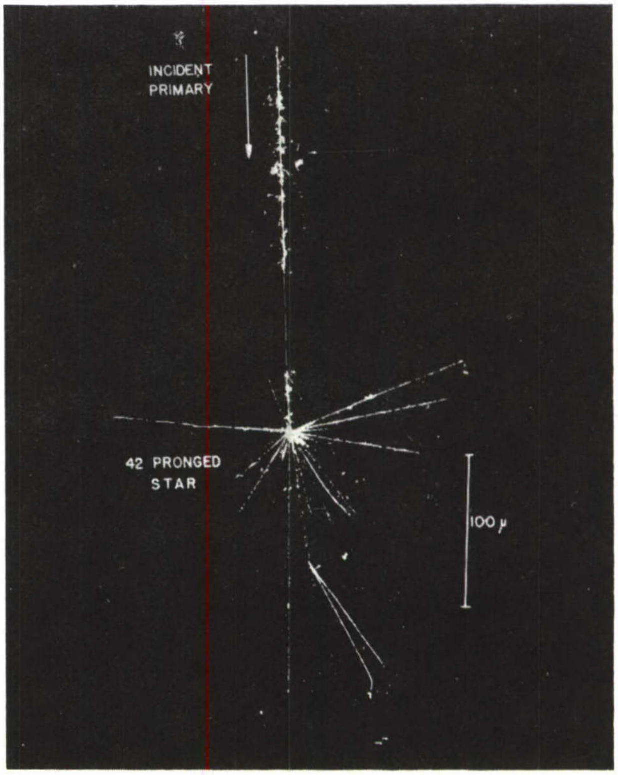


FIG. 2 TYPICAL COSMIC-RAY STAR

(From H. L. Bradt and B. Peters, Ref. 10. Courtesy of Dr. M. F. Kaplon, Dept. of Physics, The University of Rochester, Rochester, N. Y.)

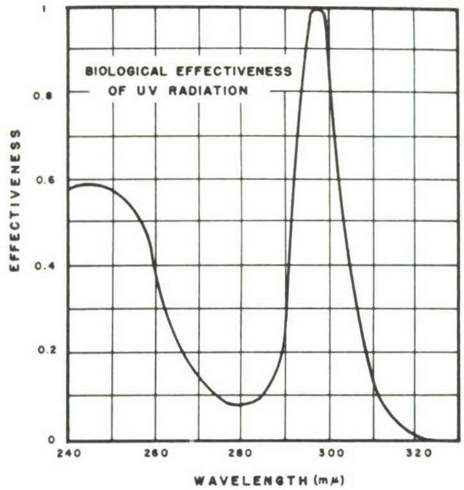


FIG. 3. BIOLOGICAL EFFECTIVENESS OF UV RADIATION

that have a pronounced effect upon the skin and the eyes by causing erythema of the skin and conjunctivitis. Fig. 3 shows the erythema producing effectiveness in arbitrary units as a function of wave length. The values given were adopted by the International Illumination Commission in 1937 (19). On the basis of these data, and by use of recent results of ozone investigations, Buettner (20) has estimated that erythema of the skin within and above the ozone layer is produced 10 to 50 times as fast as at sea level. Protection against ultraviolet radiation, therefore, is mandatory at altitudes in excess of 15 miles. Fortunately, window materials capable of absorbing these kinds of radiation are available. Upon massive irradiation by ultraviolet rays, however, most materials become turbid and discolored. Quartz, for instance, becomes brownish if exposed to large amounts of UV-radiation of a wave length smaller than 250 mμ.

E The Function of Supplying Aerodynamic Lift and Drag

It appears as though the final disappearance of aerodynamic lift at greater altitudes is of interest only to the engineer. It can be shown, however, that the absence of aerodynamic lift and drag will be responsible for a medical problem of far-reaching consequences. For, in the absence of aerodynamic and propelling forces, the crew of a high-flying rocket craft will be transposed into the state of weightlessness.

Following the reasoning of Haber (21), weight of a body can be identified with the vectorial sum of all external forces acting on the body. The same definition can be applied to the concept of "apparent weight" or "g-forces" used in aviation medicine which are usually defined as the sum of the force of gravity and the forces of inertia inherent to accelerated motion, according to the equation

$$W_a = F_g + F_i \qquad [1]$$

where W_a is the apparent weight of the body, F_g the force of gravity, and F_i the forces of inertia. Using the principle of d'Alembert

$$F_g + F_i + F_e = 0 \qquad [2]$$

where F_e is the vectorial sum of all external forces, the apparent weight or g-forces can simply be written as

$$W_a = -F_e \qquad [3]$$

The external forces comprise friction, aerodynamic lift and drag, propelling forces from an engine, and all elastic forces involved in the situation of a body being fully or partially supported. As can be derived immediately from Equation [3], a body becomes weightless if it coasts freely outside the range of the mechanically effective parts of the atmosphere.

Owing to the decreasing support which the atmosphere provides at increasing altitudes, states of reduced weight and weightlessness become increasingly more dominant in modern aviation. There can be no doubt that the phenomenon weightlessness is about to become an outstanding aeromedical problem as aviation progresses. So far, only the problems of increased body weight were of aeromedical import. Now we have reached a point where investigations of external forces acting on the body must extend into the range of reduced weight down to the complete lack of weight.

The problems related to increased body weight (g-forces greater than 1) concern primarily the interference of additional forces with the mechanical factors of circulation, respiration, dislocation of organs, body movements and their consequences. All these disturbances are, in one way or another related to elastic deformations of the body and its parts. These disturbances, up to a certain limit, vary approximately in proportion to the increase of body weight. Consequently, the elimination of body weight will probably have no decisive or even lethal effects upon the physiological functions mentioned previously. The transition from the condition of normal weight into the state of weightlessness removes the normal elastic stress exerted upon the body by its support, and there are no major indications of a possible failure of the previously enumerated body functions in the absence of this stress. The correctness of this kind of reasoning was proved by experiments with monkeys and mice in V-2 and Aerobee rockets, carried out by Henry and Ballinger (22). In several experiments of this kind, test animals were carried aloft in research rockets and subjected to the state of weightlessness during the free-flight period, lasting between 2 to 3 minutes. The rate of pulse and breathing, and breathing movements were recorded during these tests, and only slight disturbances were observed.

In contrast to the functions of purely mechanical nature, the mechanical sense organs of the body do not react to alterations of the stimulating forces in a linear relationship. They follow a logarithmic relationship which is described by the Weber-Fechner law. Therefore, we must conclude that changes of mechanical excitation in the absence of a basic stress will probably have pronounced effects on man's ability to cope with the mechanical factors of his environment in the state of weightlessness. According to Gauer and Haber (23), and Haber and Gerathewohl (24), we must expect disturbances in the function of orientation, in the proper

execution of body movements, and in the harmony of the coordination between the various components of man's mechano-receptor system. The disturbing occurrence of optical illusions, akin to the oculo-gravic illusion (33), cannot be excluded. Our empirical knowledge of the possible physiological and psychophysical consequences of weightlessness is rather fragmentary—in fact, it is practically nil. This fact constitutes a challenge to aeromedical, or better, to space-medical research.

F The Function of Supplying Diffuse Daylight

The brightness of the daylight sky at a particular point of observation depends upon the zenith distance of the sun, the difference in azimuth between the sun and the point of observation, the mean reflectivity of the earth, and—which is of particular interest here—the sky brightness depends on altitude. Haber (25) has computed the brightness of the daylight sky as a function of altitude by using the theory of Tousey and Hulburt (26). In Fig. 4 is depicted the zenith brightness in millilamberts as a function of altitude. As can be seen from the graph, the brightness of the sky at a height of 20 miles is about $^1/_{30}$ of its value at sea level. Fig. 5 shows the extension of zenith brightnesses up to altitudes of 90 miles. Although the theory of Tousey and Hulbert was not designed to stand an extrapolation to such great heights, the data given can be expected to be a fairly good approximation. According to Fig. 5, the light of the sky vanishes completely only at very great altitudes. At heights in excess of 85 miles the zenith brightness approaches that of a moonless night at sea level. From there on the blackness of space is complete.

The absence of diffuse illumination provided by the atmosphere poses a visual problem. When looking down from a high-flying craft, the eye meets brightnesses of varying degrees, depending upon the features of the landscape and meteorological conditions. Looking up, the daylight sky appears as the only source of light. Most features of the ground, the clouds and other sunlit objects are rather bright. Their brightnesses lie in the range between 300 and 10,000 millilamberts. In contrast to these values, the brightness of the sky is rather low even at moderate altitudes, and decreases further at higher levels. Owing to these conditions strong contrasts of simultaneously perceived brightnesses are produced.

The brightness contrast is expressed by the following ratio:

$$C = \frac{B_t - B_b}{B_b} \qquad [4]$$

where B_t is the brightness of the target, and B_b the brightness of the background or surrounding. Guth (27) has established contrast levels which produce an initial momentary sensation judged to be at the borderline between comfort and discomfort (*BCD*). The critical contrast values depend upon the brightness of the target, the solid angle (Q) subtended by the target, and the brightness of the background in the following fashion:

$$BCD = 108 \cdot B_b^{0.44}(Q^{-0.21} - 1.28) \qquad [5]$$

whereby the brightnesses are given in footlamberts (1 footlambert = 1.0764 millilambert). From the data of Guth it can be concluded that viewing of objects at higher altitudes will be anything but comfortable. Even at moderate altitudes, objects having a reflectance as low as 20 or 30% surpass the threshold of comfort, if they are illuminated by the sun when

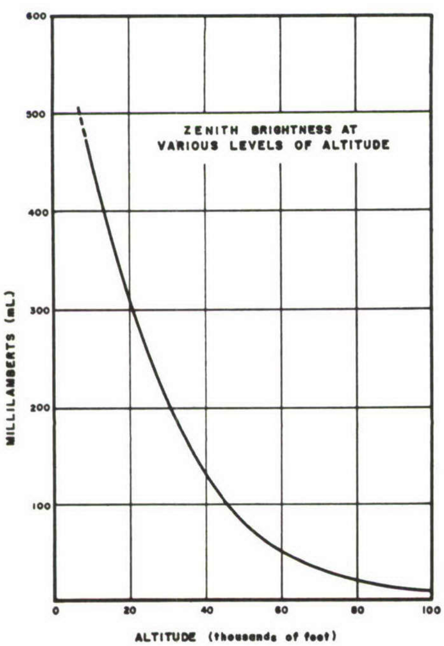


FIG. 4. ZENITH BRIGHTNESS AT VARIOUS LEVELS OF ALTITUDE

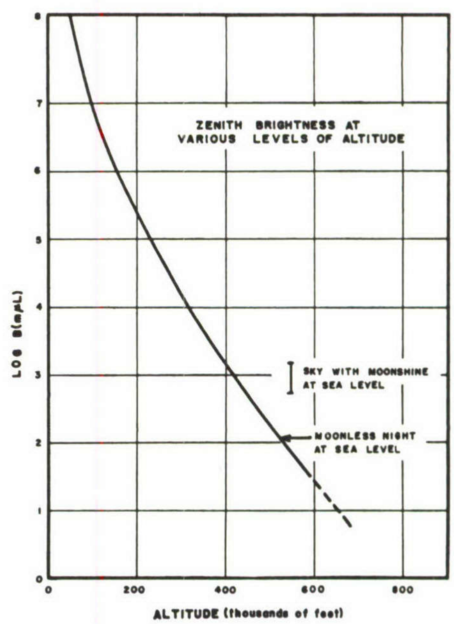


FIG. 5.
ZENITH BRIGHTNESS AT VARIOUS LEVELS OF ALTITUDE

viewed before the background of the sky. For an object the size of the wing of an aircraft, the comfort threshold is exceeded at a height of 10,000 feet, even if the reflectance of the wing surface is only 25%. At a height of 20 miles, sunlit objects as small as the disk of the moon appear too bright for comfort, if their reflectance is larger than 10%.

Far more discomfortable brightness contrasts will be encountered inside of the cabin of a high flying ship where sunlit patches will be seen adjacent to deep shadows. Owing to the small illumination of the waning light of the sky, the interior of a cabin will be rather dark. Reading of instruments will be impossible unless they are illuminated artificially. These conditions will undoubtedly cause visual discomfort, fatigue, or even disabling glare. Cibis (28) has suggested the use of light-diffusing panels covering a certain section of the window area. In this way, the interior of the ship would be shielded against direct sunlight. At the same time, such a device would provide a sufficient amount of comfortably diffuse illumination from the panel that substitutes for the loss of diffuse illumination normally afforded by the light of the sky.

G The Function of Absorbing Meteors

The hazards arising from possible impacts with meteors is of particular space-medical interest. Even moderately large meteors can easily puncture the hull of a high-flying ship—an event which would result in a very rapid explosive decompression of the crew. At altitudes accessible to man with present-day means, no hazard from meteors exist, since meteors are vaporized and annihilated at great altitudes. The great majority of meteors ranging between fine meteoric dust and particles weighing a gram or more, are absorbed before reaching the 60-mile level. Above 90 miles of altitude, however, a ship would run the same risk of being hit by meteors as in interplanetary space, except for the protection afforded by the shielding bulk of the earth.

H The Function of Interacting Thermally with the Craft

One of the most intriguing problems of modern aviation is the generation of an envelope of hot air around a fast-flying aircraft owing to aerodynamic heating. This is not the place to discuss the many aspects of the "heat barrier" which our high-speed aircraft encounter. Relative to our subject we are primarily interested in the quesion at what altitude aerodynamic or friction heating can be expected to cease. This question has been answered by Saenger (29), who has studied the stability of a satellite vehicle at various levels of altitude. He has found that, at a height of 80 miles, a satellite would lose over 6 miles of altitude per revolution as a consequence of air drag. The altitude loss per revolution would be only 3 feet, if the satellite would circle at a height of 112 miles. Somewhere in the range between 80 and 110 miles of altitude, air drag and, simultaneously, skin heating for velocities of the order of 5 miles per second will become negligible.

The temperature problems of rocket flight, however, persist even at greater altitudes. Beyond the border of thermal interaction between atmosphere and craft, the skin temperature will be determined by the exchange of radiation between the exterior of the craft on the one side, and the sun, the earth, and the cosmos on the other. Buettner (30, 31) has studied this problem in detail by calculating equilibrium temperatures of various metals and other substances. The equilibrium temperatures are calculated by equating the rate of absorbed radiant energy to the radiation losses of the body in space. The latter is proportional to the fourth power of temperature (Stefan-Boltsmann law) and to the emissivity of the body's surface in the infrared. The surprising result obtained by Buettner was the fact that all metals become excessively hot under conditions of radiative equilibrium in space, even if they are highly polished and reflecting. The high temperatures are caused by the poor emissivity of the metals in the infrared. A few of Buettner's data are given in Table 2.

TABLE 2 EQUILIBRIUM TEMPERATURES OF VARIOUS MATERIALS IN SPACE, °F

Material	Illuminated by sun	Illuminated by "full earth"
Black (soot)	252	154
White (MgO)	−60	9
Aluminum	802	563

The figures show that only gleaming white materials such as magnesium oxide can serve as surface coatings, if a manned craft is exposed to the field of thermal radiation in space.

From the standpoint of aviation medicine and space medicine the temperature problem has a further important aspect. It is the problem of survival in cases of failure of cooling systems—in other words: What is

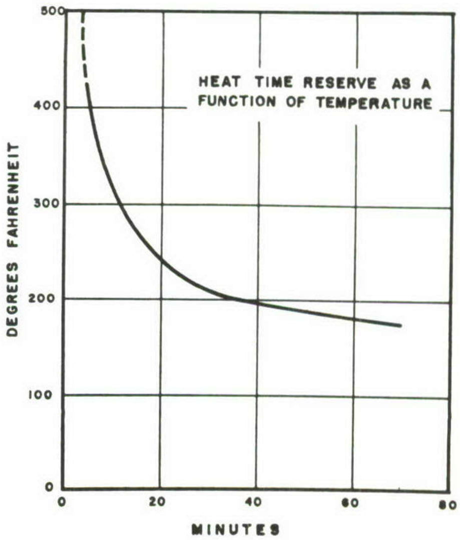
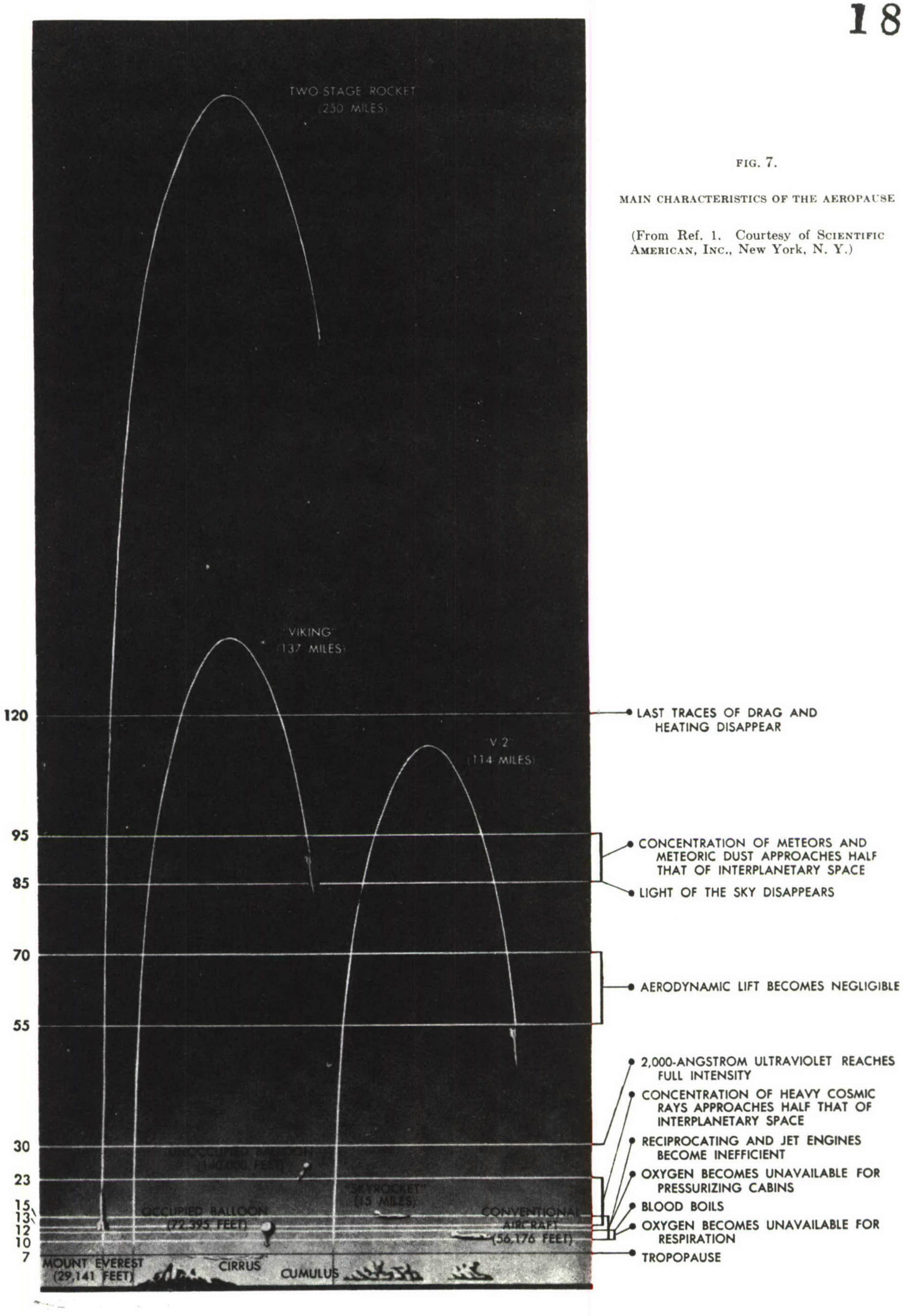


FIG. 6. HEAT TIME RESERVE AS A FUNCTION OF TEMPERATURE

FIG. 7.

MAIN CHARACTERISTICS OF THE AEROPAUSE

(From Ref. 1. Courtesy of SCIENTIFIC AMERICAN, INC., New York, N. Y.)



the time reserve of an individual more or less suddenly exposed to a hot environment? By "heat time reserve" one understands the time span that elapses between the beginning of the exposure to heat and the moment when heat collapse must be anticipated. Naturally, one must expect the heat time reserve to be dependent upon many factors such as type of clothing, profuseness of sweating, precooling of the subject, and the like. In one of his recent papers, Buettner (31) has compiled some average data which are given in Fig. 6.

I The Function of Interfering by Air Drag Over Long Periods of Time

Saenger has shown that at an altitude of 120 miles air drag has completely vanished. Beginning at this height, the establishment of a permanent satellite orbit would be possible, although a somewhat greater height would be indicated for practical purposes to allow for a certain eccentricity of the satellite orbit. Nevertheless, the 120-mile level can be considered the mechanical border of space. This line is of space medical interest insofar as above this level the state of weightlessness can be maintained for any length of time. Above an altitude of 120 miles—which, incidentally, is only about 3% of the earth's radius—the environment of space is complete.

Above an altitude of 120 miles there are only three factors of terrestrial origin that make the environment of the craft different from that found at any other point of interplanetary space: (1) The bulk of the earth which shields off half the number of meteors and cosmic ray particles. (2) The magnetic field of the earth which deflects cosmic ray particles below a certain magnetic rigidity, if they approach the earth in or near the equatorial plane. (3) The solar radiation reflected by the earth and its atmosphere, and the infrared radiation emitted by the earth proper.

The problems which arise in the operation of manned vehicles at very high altitudes and eventually in free space are of an extremely diverse and complex nature. Their solution requires contributions from meteorology, geophysics, astronomy and astrophysics, cosmic ray physics, aerodynamics, radiobiology, physiology, aviation medicine, space medicine, bioclimatology, and human engineering. Owing to these many different fields, difficulties in semantics are frequently encountered. Particularly, the term "upper atmosphere" is inadequate and misleading, since it conveys different meanings in the various fields such as meteorology, geophysics, and aviation medicine. For the common benefit it appears expedient to coin a new term for designating those regions of the atmosphere where, in terms of manned rocket flight, the conditions of conventional aviation blend into those of actual space flight. To this end, Buettner (32) proposed the term "aeropause." The aeropause is defined as that region of the atmosphere where its various functions for man and craft begin to cease and space-equivalent conditions are gradually approached. The concept of the aeropause appears to be quite useful in modern aviation and rocketry. It circumscribes the area characterized by certain factors of environment that are distinctly different from those found in the area of conventional aviation or of space. The aeropause encompasses the region between the 10- and 120-mile levels. The main characteristics of the aeropause are depicted in Fig. 7.

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BAILOUT AT VERY HIGH ALTITUDES

by

Fritz Haber

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Bailout at Very High Altitudes

By Fritz Haber, Dr. Ing.

Department of Space Medicine, USAF School of Aviation Medicine, Randolph Field, Texas

THE PROBLEMS of bailout have been frequently presented to the audience of the Aeromedical Association. Those papers gave excellent views on the practical problems related to bailout at high speeds and altitudes attained by the most modern aircraft. This paper, however, will emphasize the problems of bailout at speeds and altitudes unattainable by today's aircraft, but which will be a reality in the near future.

Before space flights are possible, there must be a flight in the borderzone of space—the aeropause—where the effects of the atmosphere on man and craft begin to cease. We should face the fact that flight in the aeropause is the next step, with speed in the range of Machnumber 10 to 20 and with altitudes in the range of 200,000 to 400,000 feet. At such altitudes the air is rarified to an extent that air pressure and density are about one millionth of their values at sea level. This means that practically all of the entire air mass is left below with the exception of only one millionth. It may be noted that such rarified air cannot provide enough lift for an airplane. Thus, the airplane must rely on the thrust of its engine or glide down, unless the speed is around 25 Mach, enabling the aircraft to coast along supported by the centrifugal forces generated by its travel around the earth.

Acknowledging the possibility of flying at very high altitudes, it is not only interesting, but also important, to ponder over the escape of a human being from a vehicle flying under such extreme conditions. One should use the fruitful principle of considering the problems by viewing them from the other side, that is, from the borders of space. Then, the scope of the problems has a very different slant, shifting the points of interest in another order of significance.

What then are the problems of escape and survival in such an environment? As outlined above, it will not be feasible to just extrapolate from the problems of today when considering the escape from an airplane flying at high altitudes.

You are all familiar with the necessity of using an ejection seat for the escape from fast flying aircraft. Such a piece of equipment enables the flyer to leave his airplane against the forces of the windblast, or more correctly expressed, against the air resistance of his own body. This force can be many times greater than the weight of the man. Therefore, it is quite convenient to express the air resistance in terms of the body's weight. The air resistance is due to the pressure forces generated by the by-rushing air. Those

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forces increase rapidly with speed, but decrease with altitude. The same holds true for the air resistance of the human body, as shown on Figure 1. This figure depicts the air resistance expressed in terms of body weight. It can be seen that at a Machnumber 10 the air resistance of the body, due to the windblast, becomes very small at high altitude. At 300,000 feet it amounts to less than one tenth of the body weight, a force which will by no means hamper a man in leaving his airplane. To get out of the cockpit will be just as easy as on the ground at a 25 mph. wind. Nobody would propose the use of an ejection seat for such an occasion.

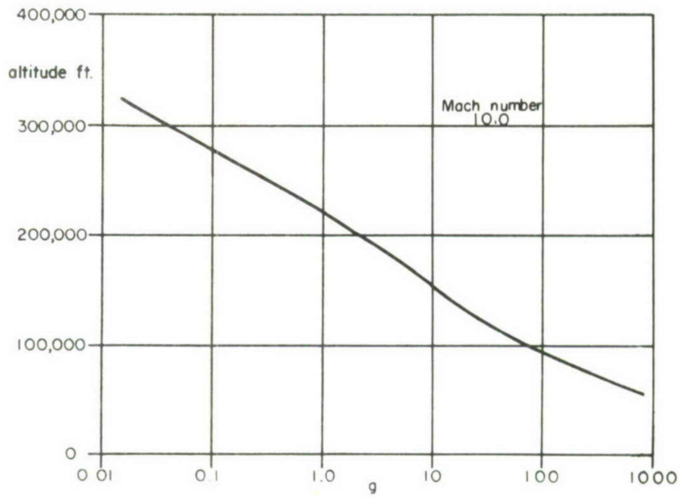

Fig. 1. Deceleration after bailout at different altitudes at a flying speed of Mach Number 10.

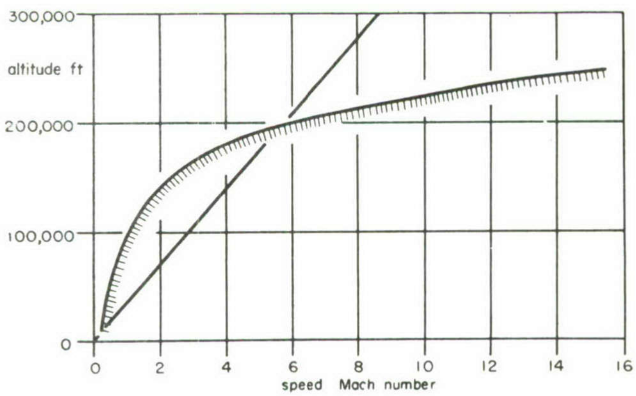

Fig. 2. Combinations of Altitude and Flying Speed Yielding a Deceleration of 1 g in Bailing Out.

If we consider a force equal to the body weight as marginal value for

bailout without the help of an ejection seat, then we can obtain combinations of altitude and speed which will produce a force of one body weight. This relation is shown in Figure 2. For combinations above the parting line, no ejection seat will be required. If we assume that the further development of flying speed and altitude proceeds along the straight line, we see that after having entered the dangerous area at relatively low speeds and altitudes, we are bound to leave it again at high speeds and altitudes. The most modern airplanes are at a point in this area where altitude and speed yield the highest forces. The future high altitudes of flight, however, will minimize these effects to an extent that they will become negligible.

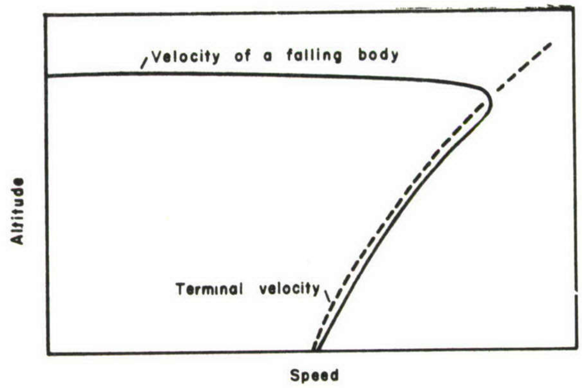

Fig. 3. Velocity pattern of a falling body.

The next phase in the escape is the free fall. You are all familiar with the fact that a falling body is accelerated downward by the attraction of the earth. Due to the increasing speed the air resistance begins to grow until it equals the weight of the body. In this state of equilibrium the body is no longer accelerated, but keeps on falling with an almost constant velocity. This velocity is called the terminal velocity, which, for a given body depends on altitude. At high altitudes the terminal velocity is greater than at sea level. A closeup study of the interplay of the force of gravity and the air resistance reveals the fact that the body overshoots the terminal velocity to a certain extent causing a deceleration.

Figure 3 shows the conditions for a free fall from conventional altitude. The velocity reaches a very distinctive maximum and tapers off again at lower altitudes, but is always somewhat greater than the terminal velocity.

A similar pattern is obtained in a free fall from 300,000 feet, however, in quite a different manner.

Figure 4 shows an example of free fall from 300,000 feet. It can be seen that the maximum velocity is very high. It is so great that we can apply the velocity terms of fast flying aircraft, that is, the Machnumber. A human body falling from 300,000 feet attains a velocity in the order of Machnumber 3. This velocity, however, is braked down very rapidly as soon as

the body hits the denser layers of the air. The deceleration—also shown in Figure 4—occurs with very high g-forces, in the order of 3 to 4 g: ance of the body. It appears as though smaller g-forces were obtained if the air resistance is decreased. This, however, is not true. A body with a small

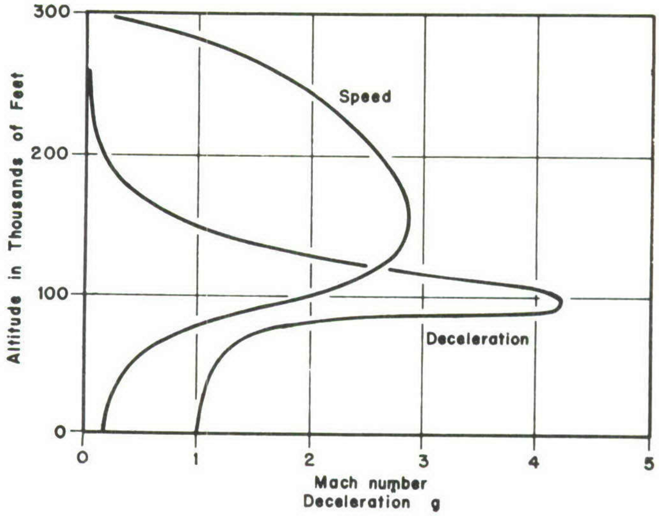

Fig. 4. Speed and deceleration of a falling body as function of altitude. Initial speed is zero.

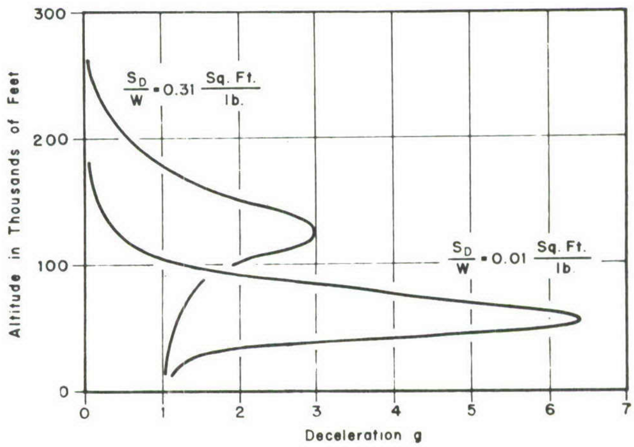

Fig. 5. Deceleration of a falling body with different air resistance.

they last for an appreciable long time, that is, for about thirty seconds. One should keep in mind, that those forces are generated solely by the air resistance picks up more speed and hits the denser layers of the air with a greater momentum.

Figure 5 shows this effect. The

g-forces are significantly greater for the body with the smaller airdrag. It may be noted, that such a body penetrates much further down into the atmosphere before losing its momentum.

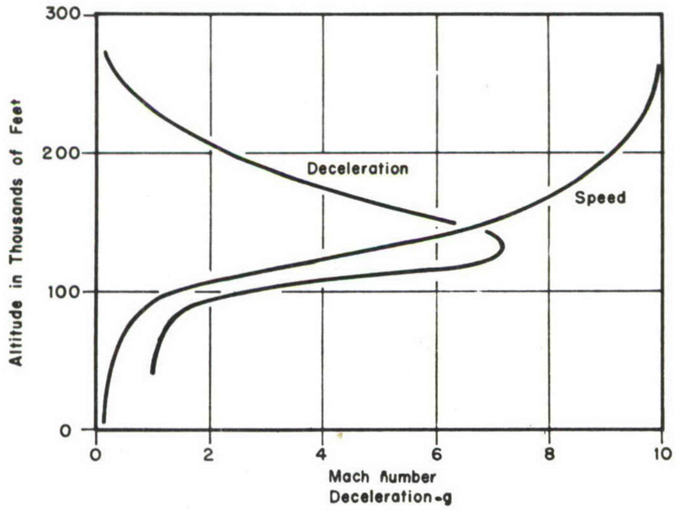

Fig. 6. Speed and deceleration of a falling body as function of altitude. Initial speed is M=10.

There is one important conclusion which can be drawn from these facts. It has recently been considered that the escape from fast flying aircraft should be performed by means of a capsule. It must be assumed, that a capsule has less air resistance than a human body. Therefore, higher g-forces must be anticipated in the phase of deceleration during the free fall. For this reason the capsule should not be designed too sleek but should have airbrakes or a small parachute for the purpose of increasing the air resistance.

The example of a falling body starting out with zero speed is well suited for showing the interplay of the different forces. However, it is a pure academic case, because it is practically impossible to drop a body from a point at rest in these altitudes. Normally, the bailout will occur from an airplane flying with considerable speed. Assuming a Machnumber 10 as initial velocity, the deceleration in the horizontal direction is in the order of one-tenth of a g. The force of gravity in vertical direction is partially offset by the centrifugal force of the circulatory motion around the earth. Thus, the downward acceleration is only about eight tenths of the acceleration of gravity.

Figure 6 shows the velocity and deceleration as a function of altitude. The deceleration is very small at the beginning, but increases significantly at lower altitudes. The maximum deceleration is in the order of 6 to 8 g. The influence of the air-resistance is the same as above, that is, a body with a small air resistance is bound to plunge deeper into the atmosphere and to experience higher g-forces in de-

celeration. Thus, the same reasoning as above should be applied to the design of capsules.

The great deceleration in this problem came somewhat unexpectedly. They are a consequence of the rapid increase in speed during the fall through the rarified air at extreme altitudes. It must be anticipated that bailout from even higher altitudes than 300,000 feet results in higher decelerations, if the body plunges into air ocean.

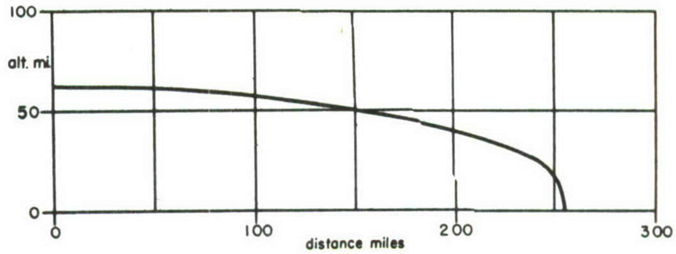

Fig. 7. Trajectory of a falling body. Initial Speed M=10.

Still another problem is posed by the g forces. At the beginning of the fall the gravity is practically zero, which means that the man is without weight. This state lasts for some time and the man will be below 1 g for a period of one minute. For the next two and one-half minutes gravity will be well over 1 g with a peak of 6 g's. It is very probable that a free falling body will begin to tumble. Since the area exposed to the windstream changes if the body tumbles, the g forces will vary according to the tumbling motion. It can be anticipated that fluctuations of 1 or 2 g will occur. Thus, the man will be subjected first, to subgravity, then to a pattern of fluctuating g forces together with the annoying forces of the rotation, a situation very likely to cause airsickness. Thus, a kind of stabilizing device is necessary to prevent the body from tumbling.

The high horizontal speed at bailout has a surprising side effect. Before the downward speed increases to a considerable value, the distance covered in horizontal direction assumes an appreciable length.

Figure 7 shows the shape of the trajectory. Before reaching the ground after bailing out at 300,000 feet at a Machnumber 10, the man travels about 250 miles in horizontal direction. For instance, a man, after bailing out over New York is bound to land in Washington, D. C.

This leads us to a specific danger involved in high altitude bailout, because the long distances traveled pose the problem of locating the man after he has landed. The search must cover an area of 500 miles in diameter and is comparable to trying to find a needle-in-a-haystack.

In discussing the physical facts of high altitude bailout, one should not forget the aerodynamic heating. A rule of thumb says that the rise in air temperature above the level of the ambient air, is about $90.M^2$ in degrees Fahrenheit. The temperature in the

airlayer around the falling body is about 80 per cent of this value. If one dares to calculate the temperature surrounding a body at Machnumber 10, one arrives at figures between 5,000 and 8,000 degrees Fahrenheit.

Figure 8 shows these temperatures occurring during the fall, and depicts the fact that the high temperatures disappear as soon as the speed decreases at lower altitudes. At first glance this appears as if the man is about to be fried, but fortunately, the heat transfer at high altitudes is very insufficient due to the low air density.

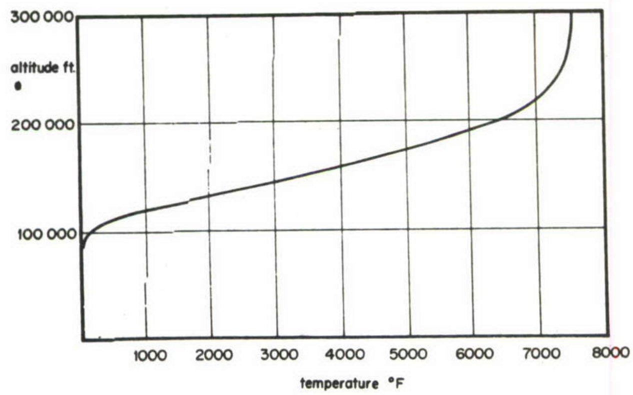

Fig. 8. Friction temperature of the air surrounding a falling body.

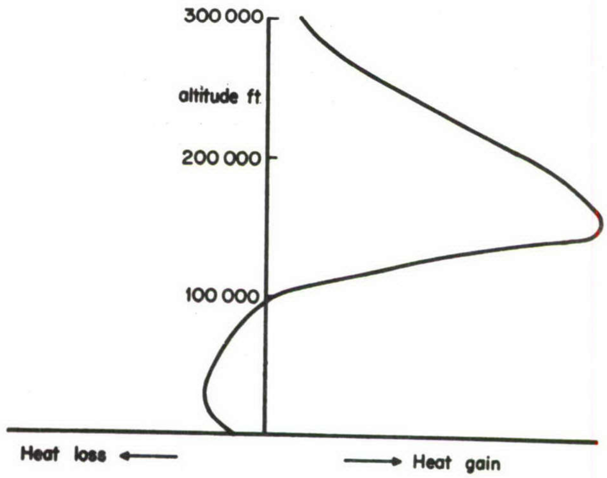

Fig. 9. Heat gain and loss of a falling body as function of altitude.

Figure 9 shows an estimation of the heat flow. It is interesting to note that the recent problems of keeping a man

warm enough after bailout at 30,000 feet, are now reversed. The heat gain is greater than the heat loss at lower altitudes, so that it is a problem to keep a man cool enough.

The following consideration gives an estimation of the heat problem involved: A body, falling from very high altitudes, attains a certain speed when it reaches an altitude of 30,000 feet. This speed is about the same as if it would have fallen from 40,000 feet. The heat loss, which is represented in the lower part of Figure 9, is known in such cases, since numerous jumps have been made from this altitude. A comparison of this heat loss to the heat gain in higher altitudes, as shown in the upper part of Figure 9, illustrates the importance of these problems.. Thus, any protective equipment must serve two purposes, that is, to keep a man cool at high altitudes and warm at low altitudes where low ambient air temperatures prevail in conjunction with low speeds.

These are some of the facts and problems one must reckon with in very high altitude bailouts. Further studies and designs are necessary to find the best equipment. As always, a compromise must be made between controversial considerations. Will it be possible to do away with an ejection seat? Is it necessary to use a capsule for the accommodation of the pilot? Or, will it be feasible to design a pressure tight space suit? Should the descent be made in two steps subsequently using two parachutes of different size? Is the time required for descent a decisive factor?

The answers to all of those questions must be found. Only a small part of them can be solved by experimentation —so, one must rely on imagination and calculation to stay ahead of things that are bound to come.

CONTINUOUS RECORDING OF OXYGEN, CARBON DIOXIDE AND OTHER GASES IN SEALED CABINS

by

Hans G. Clamann

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AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

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Continuous Recording of Oxygen, Carbon Dioxide and Other Gases in Sealed Cabins

BY HANS GEORG CLAMANN, M.D.

Department of Physiology, USAF School of Aviation Medicine, Randolph AFB, Texas

A SUITABLE CABIN environment must be provided in any aircraft carrying passengers into the upper atmosphere. The maintenance of a proper oxygen partial pressure is first in importance. Maintenance can be accomplished at lower atmospheric pressure—beginning at 6,600 feet—by increasing the oxygen percentage in the inspired air until 100 per cent oxygen at one-fourth sea level pressure (that is, 3.7 psi, 190 mm. Hg), or an altitude of 34,000 feet, is obtained. In emergencies, somewhat higher altitude may be attained by pressure breathing. However, at all altitudes higher than 34,000 feet, adequate respiratory conditions can be maintained only by compressing ambient air in a pressure cabin or by means of a pressure suit. But the application of this principle has its limits. The atmosphere eventually becomes so rare that even by the use of the most effective compressors it will not yield the desired results. These shortcomings were also apparent in the power plants of an airplane, where engines—based on external combustion—must be replaced by rocket motors that carry their own oxydizers. A sealed cabin is the only solution for the passengers. This cabin can be designed to carry sufficient oxygen in some form to provide the necessary partial pressure of oxygen for the entire flight.

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The sealed cabin—in contrast to the open system pressure cabin affording constant ventilation—calls for some means of elimination of excess water vapor, carbon dioxide and other waste gases which accumulate during flight. It is comparable to a submerged submarine in this respect. Figure I shows a comparison between the open cockpit, the pressurized cabin and the sealed cabin in regard to gas exchange with the surroundings. It emphasizes the fact that in the sealed cabin the passengers rely entirely on the oxygen in store for supply, and on absorbers for elimination of waste gases.

The question now arises as to the need for controlling the composition of this atmosphere. In answering this question some physiological data should be considered. The oxygen consumption of a normal individual depends upon the extent of muscular activity. In terms of liters per hour (STPD) the oxygen consumption is at a minimum of 15 during sleep; it rises to 47.5 at light work (as walking 2.8 mph.), and can reach as much as 322 liters per hour at record heavy work.[4] Assuming a constant exchange ratio of CO_2/O_2 of .82, the CO_2 output is 12.3, 39, and 264 respectively.

If, at the start of a flight, a cabin

volume of 70 cubic feet (1.98 m^3) of air at sea level pressure were available to each passenger, the oxygen consumption during light exercise would reduce—after two hours and six minutes—the partial pressure of oxygen in the cabin to a level corresponding to an altitude of 6,600 feet. This level would be attained, during heavy work, in only nineteen minutes. During the same time the CO_2 would reach a concentration of 4.1 per cent. The literature shows that 5 per cent could be tolerated for a few minutes only.[5] Although rocket craft can be expected to cruise at 1,000 to 2,000 mph., under operational conditions, the duration of flight will probably be as long as from one to two hours. Consequently, the fast accumulation of CO_2 within a sealed cabin must be watched. In view of this wide range of variability in gas exchange during prolonged flights, a continuous regulation of oxygen replacement and CO_2 elimination is mandatory. Only by measuring the composition of cabin air, through constant surveillance, can a regulating system be made effective.

In addition to the principal respiratory gases aforementioned, other gases or vapors generated by the occupants and the machinery in the cabin, must be considered. Here, organic solvents, hydro-carbons and sulfur compounds must also be reckoned with. Harmless though they are in small amounts, after some time they may reach a toxic level, if there is not an all-efficient absorbent. A device, giving at least a qualitative indication or detection of any such gases, would be of great help.

Regarding the choice of proper instruments for controlling oxygen and carbon dioxide, those based chiefly upon physical principles, would be most suitable. This is because they permit rapid continuous reading and

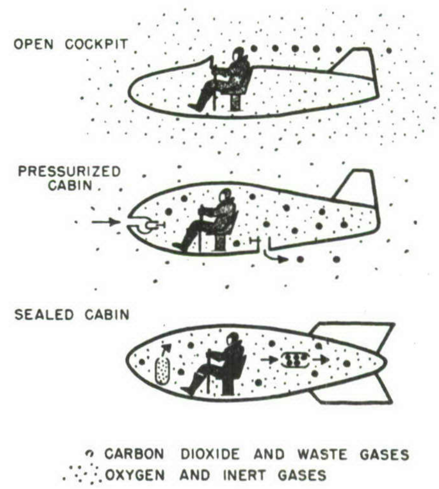

Fig. 1. Respiratory conditions existing in three types of cabins, showing supply of oxygen and elimination of carbon dioxide or waste gases. (The density of the spots simulates the concentration of molecules or the pressure.)

lend themselves to automatic control. Physical gas analyzers can be divided into two groups; namely, non-specific and specific. The measuring principle for the non-specific group utilizes physical properties that are common to all gases contained in the sample; they are distinguished only by being present in different amounts. This group comprises methods based on thermal conductivity, refractive index of light and velocity of sound. Specific methods utilize a property that is unique to an individual component in a gas mixture. Such properties are, for instance, an absorption band in the spectrum or the mass/charge ratio of ions, or the magnetic susceptibility of the particular gas.

Many of these instruments would meet the requirements for the purpose of laboratory gas analysis; however, the airplane designer would have to meet additional requirements such as light-weight, no-bulk, low-energy-consumption, and a certain ruggedness.

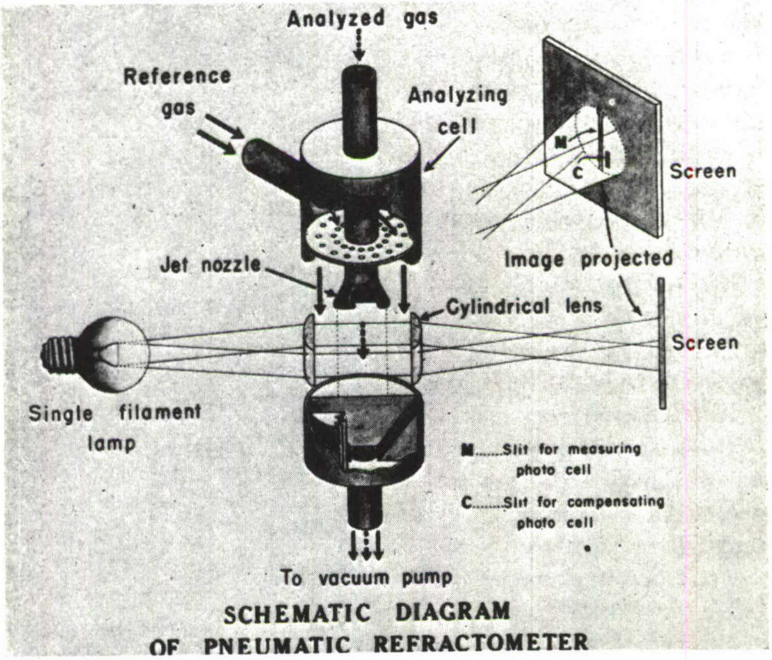

Fig. 2. The perforated disk shown in the analyzing cell, directs the reference gas to a laminar flow. The use of two photo-cells—arranged in a bridge-circuit—eliminates influence of changes in brightness of the illuminating lamp. (See text for further details.)

Under these conditions, the mass spectograph—one of the most valuable instruments—in its present laboratory form cannot be used with its weight of 1700 pounds, its 60 by 70 inch cabinet and 2800-watts power consumption, disregarding water for cooling and refrigerants.[2] If it could be simplified, this instrument would be capable of quantitative and qualitative analysis of cabin gases. Several types of infrared analyzers for CO_2 analysis have been developed but they are not rugged enough for operational use in aircraft. The oxygen analyzer, based on the principle of magnetic susceptibility, is a very reliable instrument for oxygen.

An instrument, called the pneumatic refractometer,[1] has been recently developed, from the standpoint of simplicity and flexibility (Fig. 2). Its principle is based on the fact that the refractive index of a gas is proportional to its density, or, in a mixture of gases with different refractive indices, is proportional to its concentration. The gas to be analyzed emerges from a slit-like nozzle and forms a flat band which is embedded in the reference gas. Both gases flow through the an-

alyzer cell in a laminar stream produced by a small vacuum pump. A light beam from a single filament lamp traverses the analyzer cell, directed by two cylindric lenses as windows, and finally forms an image on the screen. The brightness of the image changes, depending upon the difference in the refractive indices of the reference and analyzed gas. These changes are transmitted by photocell to a recording device or microammeter. For the purpose of checking the efficiency of a CO_2 filter, for instance, the cabin air entering the filter can be used as reference gas, while the gas having passed through the filter is analyzed gas. The latency time is limited mainly by the dead space of the connecting tubes. In the present model, the latency time is in the range of one-tenth of a second, which allows respiratory studies on tidal air (Fig. 3). For CO_2 in air, the accuracy will be about 0.1 per cent. The principle is not limited to carbon dioxide, but is applicable to other gases, depending upon their optical qualities while eliminating disturbing components.

Summarizing, it can be concluded that in order to keep these gases within their physiological limit, some kind of monitoring of oxygen and carbon dioxide in a sealed cabin, will be necessary. The longer the flight and the smaller the volume of the cabin, the greater the probability of sudden changes in percentage of the vital oxygen and carbon dioxide will be. As for instruments, simplicity, quick response and ruggedness will be preferable to accuracy. The occurrence of unpleasant gases, which may accumulate to a toxic level in prolonged flight, must also be considered.

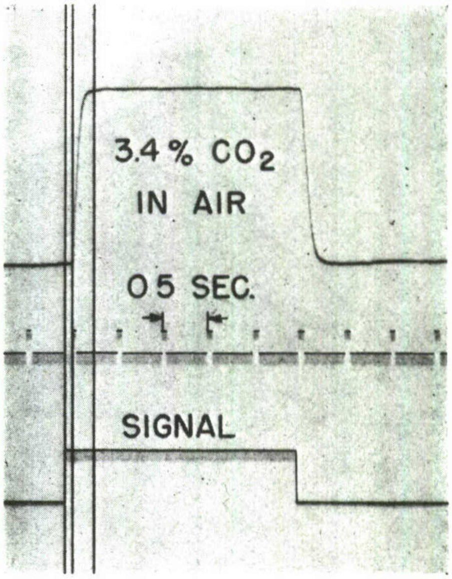

Fig. 3. Calibration curve of pneumatic refractometer. Beginning and end of signal indicates flow of the calibration gas mixture. The distance between the first vertical line (at left) and the second line marks the latency time.

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FROM AVIATION MEDICINE TO SPACE MEDICINE

by

Hubertus Strughold

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

From Aviation Medicine to Space Medicine

By H. Strughold, M.D., Ph.D.

Department of Space Medicine, USAF School of Aviation Medicine, Randolph Field, Texas

SPACE MEDICINE appears with a special program of papers, for the first time, on the public platform of a scientific society—the Aero Medical Association. For this reason, it would seem that a few introductory remarks are appropriate. It is a privilege, and indeed a source of great pleasure, that this task has been delegated to me.

Space medicine, at first glance, undoubtedly appears to many people as a capricious or whimsical idea in aviation medicine. However, upon closer examination, it proves to be a very logical step in development. When we view it from a historical standpoint, starting with the predecessors of aviation medicine, we gain a better understanding of its scope and meaning.

Aviation medicine, throughout its forty years of development, has benefited by the experiences gained in high mountain physiology. As a science, high mountain physiology is nearly one hundred years old. Mountain sickness, however, was first described by Jose de Acosta in 1588. The first mention of this uncomfortable effect of thin air can be traced back to Greek literature, since it was Aristotle who observed that men could not live on the top of the 10,000 foot Mount Olympus in Thessaly without breathing through a wet sponge. High mountain physiology, with all of its descendants, could very well claim as its birthplace, a holy mountain dedicated to Zeus or Jupiter.

Logically, Twentieth Century aviation medicine in its early years, was more or less concerned with the problems of cadet selection, reaction time, orientation, crashes, et cetera. The early issues of the Journal of Aviation Medicine tell this story. However, with the passing of time, interest in higher altitudes increased more and more. Experiments in low pressure chambers and explosive decompression chambers opened the way into the tropopause and stratosphere. Extreme explosive decompression experiments [1,6,9,12,18,19] and the medical evaluation of the balloon flight of the Explorer II[2] had already touched the area of space medicine. Aviation had attained a very high level in safety, efficiency, and comfort, as a result of the accomplishments of aviation medicine.[1,4,9,11,21] Only high-powered propeller planes and jet planes could still bring some progress in speed and high altitude flying.

It was in this situation that the first rocket appeared in the sky and—within five years—exceeded all altitude records by twenty times. This was not only a signal for the engineering world, but a challenge to all sciences concerned with the human factor. This

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new revolutionary development becomes quite clear when we review the records of altitudes reached—during the past 150 years—by means of the balloon, airplane, and rocket. We note that the balloon and airplane, both depending upon air, are—in a way—confined to two-dimensional movement in the horizontal plane around the globe, whereas, only the rocket has really conquered the vertical—the third dimension—moving away from the earth. Considered from a global point of view, this shift in dimensions is the most conspicuous mark in the new development of flight. A new frontier has now been opened—the "vertical" frontier.[5]

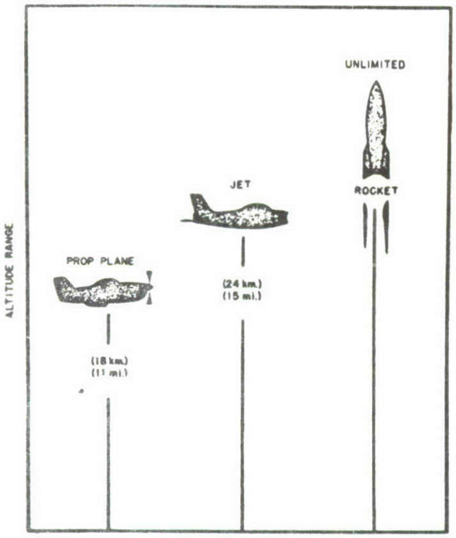

Fig. 1. The vertical extent of the operational areas of propeller, jet, and rocket craft.

Figure 1 shows the vertical extent of the operational areas of propeller, jet, and rocket craft. The ultimate limit for propeller-driven planes is about 18 km. or 60,000 feet; for jet planes, about 24 km. or 80,000 feet; and rockets are limited only by their fuel capacity. With regard to speed, propeller-driven and jet planes have attained velocities in the neighborhood of the speed of sound. Rockets have practically no limitations of speed.

The limiting factor in height and speed, for conventional planes including jets, is the atmosphere. However, in the realm of the rocket, flying is no longer dependent upon air as a supporting medium. Thus, the factors with which we must deal in rocket flight are not properties of the atmosphere, but rather attributes of free space.

For this reason, a most logical step, and a daring one too, was the creation of a new branch of aviation medicine, space medicine. In anticipation of this development, a special department, the Department of Space Medicine, was founded in 1949 by Major General Harry G. Armstrong, at that time Commandant of the USAF School of Aviation Medicine at Randolph Field, Texas. Problems concerning rocket flights were also being studied by the Aeromedical Laboratory at Wright Field about the same time.

The first open discussions in the field of space medicine were held at two earlier meetings, one called by General Armstrong in 1948 at the USAF School of Aviation Medicine, Randolph Field, Texas[3] and another organized by Dr. Andrew Ivy and Dr. John D. Marbarger in 1950 at the University of Illinois in Chicago.[20]

At the 1950 meeting of the Aero Medical Association in Chicago, the creation of a Space Medicine Branch of this organization was proposed; and

at the 1951 meeting in Denver, this branch was finally established with Colonel Paul A. Campbell as its chairman. The foundation of this branch was a necessity in order that we could have a medical counterpart of the various rocket societies, space flight societies, astronautical and interplanetary societies, which are exclusively technical in nature. It must be recognized that these societies, which exist in more than half a dozen countries, have shown great activity and success during recent years. The human factor in space flight, however, is as important as the technical factor.

Today the Space Medical Branch of the Aero Medical Association offers a special program. Space medicine is no longer the diffuse area which it may have appeared to be a few years ago. The scope of its problems is now clearly defined. They have been clarified by the introduction of a new concept of the boundaries between the atmosphere and space, based on the function which the atmosphere has for man and craft.[13,23] This functional consideration demonstrates that at relatively low altitudes the various functions of the atmosphere cease, one after the other. Consequently, the various space factors take over. Such levels are properly called space equivalent altitudes (Fig. 2). In mentioning only a few of them, we meet space equivalent conditions with regard to

Anoxia at 52,000 feet;

Body fluid boiling at 65,000 feet;

Heavy primaries of cosmic radiation at 120,000 feet[22,16]

Ultraviolet solar radiation at 135,000 feet;[17]

Optical appearance of the sky at 400,000 feet;[13] and

Meteorites at 500,000 feet.[24]

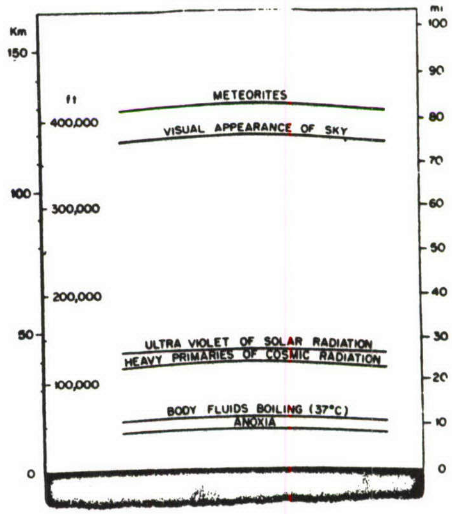

Fig. 2. Space equivalent and semi-equivalent conditions within the earth's atmosphere. (For further details see text).

It may be added that only the earth with its magnetic field, its radiation and its bulk, modifies some of these conditions, making them different from those found at greater distance. Since the bulk of earth affords protection from one-half of the cosmic radiation and meteorites, we may, in these particular cases, speak of semi-equivalent conditions of space.

Space equivalent stages within the atmosphere must be considered in regard to the necessity for sealed cabins, and also with regard to pure radiation climate above a certain altitude.[7] Further, conditions characteristic of space originate in the motion of the craft; here, weightlessness is the most outstanding phenomenon.[8,14,15] This prob-

lem was first discussed by H. Haber in a seminar at the Aeromedical Center in Heidelberg in 1946.[10]

This approach, based on a functional concept of the atmosphere, clearly indicates that a differentiation must be made between two distinct regions of the physical atmosphere: the lower section is the realm of conventional flight where the properties of the atmosphere can be utilized; the upper section, beginning as low as 50,000 feet, where the functions of the atmosphere gradually become ineffective, has many properties in common with free space. It is indeed amazing to observe that various environmental factors of space penetrate down to rather low altitudes. The usable portion of the atmosphere is a very thin shell. The so-called upper atmosphere of the physicist is equivalent to free space, for all practical purposes.

A symposium on the physics and medicine of the upper atmosphere was held in San Antonio, Texas, in November, 1951.[25] This meeting, which was organized by Brigadier General Otis O. Benson, Jr., Comandant of the USAF School of Aviation Medicine, and Dr. Clayton S. White, Director of Research of the Lovelace Foundation, must be considered an important step toward clarifying the medical problems involved in flight in the highest strata of the atmosphere, where the various benefits derived from the presence of air fall short. The problems of flight in this area are different from those encountered in free space. For this reason, the area was designated by a special term, namely, the aeropause (K. Buettner).[25] In a way, flight at present is in an amphibian stage, in a phase of transition between conventional aviation and future space flight.

The technical development clearly points to the final conquest of free space. We must be prepared to meet the necessities of this day. The field of space medicine must in time be promoted to eventually cope with the human problems which will most certainly arise.

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PHYSICS AND PSYCHOPHYSICS OF WEIGHTLESSNESS: Visual Perception

by

Siegfried S. Gerathewohl

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AIR UNIVERSITY
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Physics and Psychophysics of Weightlessness
Visual Perception

BY SIEGFRIED J. GERATHEWOHL

Department of Ophthalmology, USAF School of Aviation Medicine, Randolph Field, Texas

IN A PREVIOUS paper the attempt was made to elaborate some physical and psychophysical principles which determine the behavior of the human body under conditions of partial or entire lack of weight.[35] It was shown that subsequently to a transition of the body into the gravity-free state the field of elastic forces acting in the interior and on the surface of the body will attain a new state of equilibrium, in which the sum of all elastic forces acting on each point of the body's interior and surface vanishes. In this situation the stimulation of the vestibular apparatus is changed decisively; probably accompanied by the sensation of falling freely. One may assume that this sensation will prevail as long as the individual is not adapted. If adaptation takes place, the individual's situation will be accepted as a new psychophysical zero-state. The consequences of this transition with regard to the stimulus-sensation relationship also was discussed.

The entire range of phenomena treated in the above-mentioned paper was related exclusively to the stimulation of the mechanoreceptors. Other perceptual cues, especially visual ones, were considered but little. It is the rationale of this paper to arrive at some theoretical conclusions concerning the interaction of the proprioceptive and visual senses under conditions of sub-gravity and zero-gravity.

One may object that a study of this intricate problem on a purely theoretical level is not warranted at this time. It is believed, however, that an attempt of this nature is of value for a number of practical and theoretical reasons:

1. The phenomenon of reduced or eliminated weight is about to become an important environmental factor of man with the advent of the high-altitude, high-velocity craft. In a modern fighter or rocket plane the pilot is likely to experience kinematic conditions which involve the reduction or even entire loss of weight.[36]

2. The effects of increased weight on man were studied thoroughly during the past decades. No or only little efforts were made, however, to investigate the effects of decreased weight on the human organism.

3. The medical and psychological literature makes available a wealth of information about the relationship between proprioceptive and visual senses, which can intelligibly be used for an extrapolation to the conditions of sub-gravity and zero-gravity.

Opinions or conclusions contained in this report are those of the author. They are not to be construed as necessarily reflecting the views or the endorsement of the Department of the Air Force.

In the field of space medicine* a number of basic concepts and terms came into usage which are of necessity for the understanding of our problem and which will be defined briefly for the benefit of the reader:

1. *Weight.*—Within the gravitational field of the earth a body derives its weight from the mechanical support that prevents it from falling freely. On the other hand, a body is weightless as soon as it is allowed to move freely under the influence of gravitation and its own inertia. In this case, the body finds itself in accelerated (decelerated) motion along a Keplerian trajectory, and the resultant of the forces of inertia exactly compensate the gravitational pull directed toward the center of the earth (see reference 36, p. 389, Fig. 2).

2. *Gravity.*—Gravity is the vectorial sum of the forces of gravitation and inertia acting on a body. In this sense, gravity is synonymous with weight. According to the Newtonian relation: force = mass x acceleration, the force of gravity is measured most conveniently in terms of acceleration, with the acceleration due to the terrestrial gravity $g = 981$ cm. sec.$^{-2}$ as the unit. Normally, with a body being at rest, the forces of inertia are absent and the body finds itself in the "normal state of gravity" of $g = 1$.

3. *Sub-gravity.*—If a body is subjected to a downward acceleration smaller than 1 g, the forces of inertia associated with acceleration are subtracted from the gravitational force acting on the body. In this state, the body finds itself in a state of subgravity. Similarly, if a force of inertia is added to the gravitational force, such as is on a centrifuge or at an upward directed component of acceleration, the forces involved add vectorily and produce a state of "super-gravity," i.e., $g > 1$.

4. *Zero-gravity.*—In the special case that a body is subjected to a downward acceleration of 1 g, the forces of inertia exactly eliminate the force of gravity and the body finds itself in the state of zero-gravity. This case is realized in all motions of unpropelled bodies in ideally frictionless space.

Possible methods of producing these states for research have been outlined elsewhere.[36] Here, we may only mention the fact that within the gravitational field of the earth gravity can be reduced or removed by kinematic means. Although the problems connected with weightlessness are of first importance in aviation, the behavior of perception under conditions of reduced gravity is of general interest. In view of this, we invite the attention of the reader to the possible effects of zero-gravity on vision. It is the purpose of this paper to gather some data obtained under conditions of more and less than 1 g and to apply these findings to our problem.

PERTINENT ANATOMICAL AND PHYSIOLOGICAL DATA OF THE EYE

Since we are dealing with partial or entire lack of weight in this study,

*Space Medicine: The human factor in flights beyond the earth. Ed. by John P. Marbarger. The University of Illinois Press, 1951.

these functions directly related to mechanical characteristics of the body and its parts, will be of first concern. As to the problem of visual perception, the anatomical and structural characteristics of the eye will be discussed first, for it is from the mechanical side of the optical sense organ that alterations of perception may eventually be expected.

As is generally known, the human eyes are slightly asymmetrical spheres inclosed by the sclera and the cornea. Both inclosures are relatively rigid and unelastic providing a stable hull for the eye. The weight of the eyeball is about 7 grams, its volume about 6.5 cc., and its specific gravity varies from 1.02 to 1.09.[15]

Within the eye a hydrostatic pressure of about 20 to 25 mm. Hg is maintained under normal conditions. There is always an equilibrium between the intra-ocular pressure, the tention of the tissue and the blood pressure so that an adequate circulation is secured. Disturbances of the equilibrium can be balanced by the safety mechanism of the canal of Schlemm. Since the latter is relatively small, the intra-ocular pressure may be varied by altering the volume occupied by any of its content. A dilatation of the capillaries, for instance, brings about a transitory rise of pressure, and their contraction a corresponding fall. So, if osmotic or mechanical forces act upon the intra-ocular pressure, a reactive system of mechanical and nervous processes serves to re-establish the normal pressure.

The action of the external muscles also influence the intra-ocular pressure in such a way that the latter is raised when the muscles of the eye are activated and that the pressure falls when these muscles are paralyzed.[15] No direct relation, however, exists between the intra-ocular pressure and the intra-cranial pressure. In the following a description of the physiological processes in the eyes in relation to acceleration is given as a simple model only; actually, these processes are much more complex. At any rate, this model is thought to depict the circumstances affecting perception under conditions of un-normal acceleration.

"Positive" Accelerations. — During changes in acceleration only organs of considerable mass are subject to stress due to increase of weight. As to the fluids within the body, the blood and the cerebrospinal fluid need special consideration. Centrifugal forces acting in the direction head-to-seat bring forth a hydrostatic pressure differential along the large vessels and in the cavities of the body. Below the heart, the efferent blood flow is facilitated while the venous inflow becomes difficult. Above the heart, the conditions are reverse. On the other hand, forces acting on fluid contained within the ventricles of the brain or in the subarachnoid spaces may give rise to disturbances of the intra-cranial pressure.

The failure of the circulation to the head due to centrifugal force results in ischemical hypoxia of the brain and probably of the retina and consequently in the disturbance of vision. As soon as the pressure in the retinal artery falls below the normal

intra-ocular pressure, the artery is compressed by the prevailing pressure of the intra-ocular fluid and the retina fails to function due to circulation disturbances. Proper circulation is maintained to about 4 g. From here on, a distinct diminution or a complete loss of vision commonly known as "black out" may occur. As the acceleration is decreased vision returns quickly.

"Negative" Acceleration. — During negative acceleration (seat-to-head) a reversal of the processes described above takes place. Then, the blood pressure rises according to the seat-to-head direction of the acting force, and the hydrostatic pressure produced in the carotid arteries acts in the same direction as the force of the heart. Consequently, there is little inertia to be overcome and both forces give rise to the high pressure: the lids and the eyes are congested and swollen, the vessels of the conjunctiva stand out prominently, and subjunctival hemorrhages have been described.[58]

From both types of acceleration it may be concluded that the eye is affected but indirectly by mechanical forces. There are no data available that vision may be affected directly when the centrifugal force acts on the eyeball.

Accelerations Smaller Than 1 g (Sub-gravity and Zero-gravity).—The weight of the body and its parts will decrease or vanish under the condition of sub-gravity or zero-gravity, respectively. At the same time weight of the eyeball and intra-ocular pressure will be changed. Fortunately, however, these changes will be relatively small and unimportant as to their effect so that no disturbances in vision may be anticipated.

During sub-gravity the weight of the total amount of blood will decrease, and during zero-gravity the weight of the blood will vanish entirely. This reduction of the weight may cause an increase in blood pressure in the vessels located above the heart and a decrease of pressure in the lower part of the body. If the system of the blood vessels would operate as a rigid system of pipes, the loss of weight and the increase of the systolic pressure might affect the blood circulation. Since, however, the vessels vary as to their capacity due to the elasticity of the walls, part of the increase in pressure will be abolished within the system of the blood vessels. Furthermore, the systolic work of the heart muscles acts directly on the amount of blood in the left ventricle only indirectly but to a much larger amount on the resistance of the blood during its circulation through the vessels. It is this effect which causes the hydrostatic pressure within the blood vessels, while the volume of blood in the heart is only of minor importance for the total amount of pressure. An increase of the blood pressure in the skull and consequently in the eye produced by weightlessness would also necessarily require that no nervous regulation takes place beforehand.

We know, however, that the human organism is able to compensate alterations of the hydrostatic pressure and of the blood volume. This is chiefly accomplished by the influence of the carotid-sinus reflex upon the tonus of

the vessels and upon the speed of pulsations.[58] By this it becomes evident that the body possesses a system of regulators for balancing the small disturbances which may occur by the lack of weight of the blood. Practically, these regulation mechanisms become active already during 1 g conditions when the body is in any other than a vertical position. When lying horizontal for instance, the mechanical conditions as to the circulation of the blood in the body and in the head are changed considerably compared to the standing or sitting position, respectively. Nevertheless, no significant alteration in blood pressure does occur. Hence, no disturbances of vision caused by the effects of zero-gravity on the blood are expected.

Similarly, the loss of the weight of the eyeball will not have a disturbing effect on visual perception. The pressure or weight, respectively, of the liquid of the eye on its support is only a fraction of the hydrostatic pressure within the eye, which, therefore, will remain fairly constant in the subgravity and zero-gravity state.

Finally, the influence of weightlessness of the eyeball on the external eye muscles must be considered. There may be some disturbances in the balance and control of eye movements due to the cessation of weight; but we have some reason to assume that the balance will be restored very fast. Again, the weight of the eyeball in relation to the rigidity of its structure is so small that no pronounced effects are anticipated.

Consequences of the weightlessness of the brain, if any, may eventually influence visual perception. The alterations of the intra-cranial pressure, for instance, may be of greater importance due to the larger dimensions of the brain and the cranial liquid. Hence, these alterations may cause deteriorations of the activity and the proper functioning of the brain, which may seriously impair the perceptual processes. The possible neurological and psychological aspects thereof, however, are beyond the objective of this paper.

ORIENTATION UNDER CONDITIONS OF VARYING GRAVITY

Normally, man lives under conditions of 1 g, and most of his phenomena of life come to pass in the three-dimensional space. In this environment he has to orient himself; and in order to do so, a system of references must be at his disposal. The main determinants of this system are of optical and gravitational origin. They furnish the frame of reference within which the spatial orientation takes place.[19,21,37]

By orientation, the ability of the individual to localize his position with reference to the three-dimensional space is understood, in which the act of localization is guided by a complex of perceptions. It is this complexity, and the role of visual perception for space orientation, which requires an investigation of this problem from the standpoint of zero-gravity.

Visual Spatial Orientation

In another paper an attempt was made to demonstrate that the visual perception of depth is indispensably based upon the elements of space, time and matter.[9] For the determination of an object in space its position in the

two-dimensional visual field of the observer and in depth is necessary. The act of localization, then, will be made by means of all orientational cues available.

1. *Under Normal Conditions.*—The crucial indices for the localization of the body or of an object within the two-dimensional plane of observation are the vertical and the horizontal directions, which can be determined by the individual with great accuracy. Jastrow (1893) found that the average error in judgment of the visual vertical and horizontal was less than 0.6 degree deviation from the true position; whereas the mean error of judgment of lines tilted at an angle of 45 degrees amounted to 4 degrees in a direction toward the horizontal.[38]

Koffka (1935) states that the precision in the perception of the visual vertical is due to the development of a visual spatial framework which he calls an "anchorage in space."[41] More recently, Mann and Berry (1949) investigated the accuracy with which the individual is able to determine the vertical and horizontal by setting a target (two 8-inch parallel strings treated with luminous paint and illuminated by an ultraviolet lamp) to that position.[47] They found that the mean errors of judgment were less than 1 degree for each subject and that there was no significant difference between the errors in judgment of the visual vertical and the visual horizontal.

From this one can conclude that the individual is able to judge the visual vertical and horizontal with a considerable accuracy under normal gravitational conditions.

2. *In Situations of Postural Conflict.*—Already Aubert (1860) noted that when an individual views an upright visual target with the head tilted there is an apparent rotation of the vertical target in the direction opposite that of the inclination of the head.[4] Later, Mueller (1916), when repeating Aubert's experiments, found that a vertical line appeared tilted in the same direction as the head when it was tilted only by a small degree; but that for large amounts the Aubert phenomenon is valid.[52] Passey (1950) and Passey and Ray (1950) confirmed both Aubert's and Mueller's findings up to 20 degrees, insofar as some of their subjects noticed the Aubert and some the Mueller phenomenon.[54,56]

Witkin and Asch (1948) placed subjects in positions of head and body tilt and measured their ability to establish the true vertical.[68] From an angle of 45 degrees the mean deviation from the vertical was about 6 degrees during head tilt. Three positions of body tilt were employed: 28 degrees, 42 degrees and 90 degrees, the average errors being 7.6 degrees, 5.9 degrees and 16.1 degrees, respectively. In a later experiment, Witkin (1950) used a tilted room instead of the target.[67] The errors were much greater than in the foregoing experiment (mean error from a position of 22 degrees amounted to 12.8 degrees and 22.3 degrees, when the room was tilted either in the direction of body tilt or in the opposite direction, respectively), and this can be interpreted as a tendency of the subject to accept the tilted room as vertical.

Passey (1950) reports a significant increase in mean and constant error

with increase in magnitude of body tilt. The mean average errors range from 1.6 degree at 5 degrees to 2.9 degrees at 20 degree tilt; the mean constant errors from 0.4 degree at 5 degrees to 2.3 degrees at 20 degree tilt. He thus concludes that in conditions of conflict, adjustments were made more nearly to the gravitational vertical than to the tilted visual framework.[54]

Finally, Ray and Niven (1951) confirmed the hypothesis that postural cues dominate over visual ones in the perception of the true vertical. Moreover, postural factors were found to influence the judgment of the visual vertical, whereas no modification of the postural vertical by visual factors was demonstrated.[57]

Summing up the findings it may be said that body tilt alone, up to a magnitude of 20 degrees, does not seem to impair the perception of the visual vertical. With tilts of higher degrees, however, vertical orientation appears to be influenced as much by the degree to which the individual identifies himself with the tilted visual as by the body tilt itself.[46]

3. *Under Conditions of Visual Conflict.*—Visual perception under conflicting visual cues is no paradox, but it may occur under certain static and dynamic conditions.

Wertheimer (1912) reports an experiment in which the image of a room was tilted by means of a mirror at an angle of 45 degrees.[65] The room appeared at first tilted, but soon it appeared vertical and the floor horizontal. Under similar conditions Asch and Witkin (1948) observed an apparent tilted room and had the vertical set to the true position.[2] The total tilt of the frame of reference was 30 degrees; the mean value of the errors amounted to 21.5 degrees. Wertheimer's experiment was also repeated by Gibson and Mowrer (1938) who found that the room appeared tilted, although the amount of tilt seemed to decrease with time.[25] They, therefore, conclude that there is an adaptation to the inclination, which makes the picture appear more natural but will not eliminate entirely the impression of tilt.

In another experiment Asch and Witkin (1948) tested Wertheimer's theory that with continued observation the mirror image of the room appears to right itself.[3] They found that during an observation time of six minutes the mean errors of the vertical and horizontal increased only slightly. About 50 per cent of the subjects perceived the complete righting of the room.

The effect of adaptation to visual tilt was investigated by Gibson and Radner (1937).[26] They found that the amount of tilt decreased with the increase in observation time. There was a considerable adaptation effect with five seconds observation and an increase up to 45 seconds; then, the curves flattened out. Recently, Passey (1950) and Passey and Ray (1950) reported that with increasing amounts of tilt there is an increase in the size of the average error of adjustment and an increase in the amount of constant error in the direction of the tilted room.[54,56]

By a critical perusal of the findings given above the hypothesis of Koffka,

Wertheimer, Asch and Witkin that the main lines of visual space are of most importance for the determination of the vertical and that in case of visual conflict these lines are accepted as determinants of the vertical to the neglect of gravitational and postural guidances must be doubted. One is inclined to suspect that the adjustment to one set of the cues is more or less the result of "projection or identification" rather than the result of a true perceptual change.[46] On the other hand, it was demonstrated by these findings and by Evert's results (1930 and 1937) that vision can be adjusted to all kinds of changing circumstances.[16,17] From this, one must agree that visual perception is labile, when the perceptual conditions are altered by decreasing the number of cues or by introducing contradictory cues causing situations of conflict.

Non-visual Spatial Orientation

Under favorable conditions the intact organism will make use of all appropriate cues for the maintenance of the equilibrium and the determination of the postural vertical. After the visual cues, labyrinthine and proprioceptive cues are most important for the orientation in space. A reduction of the number and quality of the cues will result in a reduction of the precision of postural determinations. Since we have seen that visual orientation proved to be labile under certain conditions, it seems to be indicated to investigate now the reliability of non-visual space perception.

1. *On the Ground.*—Early investigators as Burt (1918), Garten (1920), Backhaus (1920), Gemelli, Tessier and Galli (1920), Fisher (1923), and Kleinknecht (1923) found that individuals are able to maintain and restore their equilibrium as well as to judge the vertical and horizontal in the absence of visual cues with a high accuracy (average error 1 degree or less). They report only a slight amount of improvement of the results due to practice.[5,8,20,22,23,40]

Recently, Mann and Dauterive (1949), and Mann and Berry (1949), tested the ability of the subject to judge the gravitational vertical from positions of lateral tilt (5 to 90 degrees).[47,48] They found a mean variable error of 1.9 and 3.2 degrees, when he had to turn himself back into the vertical and when he had to signal the vertical position while moving, respectively. The constant error for both conditions was 0.8 degree and 2.4 degrees, respectively.

When individuals are placed in position of tilt and are required to return themselves to the postural vertical without visual cues, there is the possibility of occurrence of adaptation. Passey and Guedry (1949) report this effect as an increase in tilt from the true vertical and in the numbers of errors in direction of initial inclination.[55] Delay in readjustment also served to produce significant difference in variability.

The effects of varying duration of exposure upon adjustment to the true vertical were confirmed by Mann, Passey and Ambler (1950).[50] As far as variability is concerned, they are in conformity with Mann and Passey's results (1949), who found no increase in variability with delay as opposed to

immediate readjustment.[49] The latter studied the adaptation effect to tilt under modified and nonmodified somesthetic conditions. They succeeded in proving adaptation to postural inclination by a shift of the constant error toward the direction of initial tilt and by an increase in the number of errors in the direction of inclination.

By the experiments described above it becomes evident that under these conditions the individual is able to make accurate judgments of the postural vertical in the absence of visual cues. Delay in readjustment, however, brings forth an adaptation effect which is expressed as decrement of the accuracy of postural orientation. The same effect was produced by a modification of the somesthetic cues. This justifies the assumption that the nonvisual postural orientation will be endangered after support and weight are abolished in the gravity-free state.

2. *Under Flying Conditions.*—Van Wulfften-Palthe (1922) was one of the first to investigate the problem of postural orientation in aircraft.[69] He found with untrained subjects, as well as with trained pilots, that in none of the test series was the correctness of the judgments greater than would be expected by chance. Even the relatively high angular accelerations during loops and rolls were not perceived by the individuals and it was only during spinning (about 120 degrees per sec.) that marked sensations of motion and posture occurred

In 1931, Tschermak and Schubert experimented with a luminous line in the aircraft and found that with a lateral inclination of 40 degrees the apparent vertical deviated from the true vertical at an angle of 6 to 10 degrees.[60]

The ability of the individual to judge his posture in flight was also investigated by Jones, Milton and Fitts (1947). Experienced pilots of the Air Force were used as subjects. They were required to judge the attitude of the plane during a series of simple maneuvers. The average of erroneous statements amounted to 39 per cent. With certain maneuvers the errors increased up to 80 per cent. They also observed effects of adaptation as described above.[39]

At about the same time, MacCorquodale (1946) studied the nonvisual perception of motion and body position during flight.[42] He reports that nonvisual spatial orientation is subjected to gross limitations and to deceptions. The perception of turning and tilting appears after a considerable time lag from the onset of the maneuver, the direction of bank and turn may be erroneous, and the estimates of amount of bank are markedly depressed. Perceptions of both tilting and turning are transient and disappear before the plane recovers. The recovery is accompanied by sensations of tilting and turning away from the direction of the preceding turn, which persists into the period of following straight and level flight.

Additional data were collected by MacCorquodale, Graybiel, and Clark (1946) on the nonvisual orientation problem after it was found that a strong sensation of backward tilt occurred during a turn, and forward tilt on recovery from a turn.[43] It could be shown that this feeling of tilt is in-

dependent of the angle of attack in starting the turn and that adaptation effects also became evident.

The effects of linear acceleration and deceleration on the flyer's spatial orientation in the absence of visual cues were investigated by Clark and Graybiel (1947).[10] Strong sensations of tilt were reported in both cases during flights in an SNJ-6 type aircraft. The tilt was always in the direction of the resultant of the accelerative or decelerative forces, respectively, and the force of gravity.

These results demonstrate that the perception of posture and position during flight is relatively difficult. Without visual cues it is almost impossible to make precise judgments of the true vertical and horizontal with respect to the ground. Position orientation in flying is a function of the resultant of the force of gravity and the accelerative force acting on the body.

Visual and Gravitational Conflict

Through the presentation of the data and the discussion of the result given above it should be made clear that the problem of orientation must be seen in the role of visual and gravitational factors for the perception of space. It is still a controversal question whether, in the event of conflict, one set of factors would predominate in the determination of verticality.

The answer to this question will be of importance for the problem of orientation in the state of weightlessness. If, on the one hand, it could be proved experimentally that visual perception is the dominating factor in postural orientation, the chances would increase that the normal orientation scheme could be maintained without serious difficulties after the modification of the somesthetic cues brought about by the lack of weight. If, on the other hand, gravity is the prime factor, vision may not prove so stable to withstand the effects of zero-gravity.

The problem seems to be serious enough to be inquired in detail. First of all we must consider the methods, which can be used for provoking a visual and gravitational conflict. In order to establish a conflict situation, the magnitude of gravity—not only its direction—should be altered. In the first case, one obtains a real conflict between vision and gravitation; in the second case, contradictory visual and postural cues are present which were dealt with in the last paragraph.

1. *On the Human Centrifuge.*—The factors involved in space orientation when gravity is changed by adding a horizontal centrifugal force were studied by Mach (1873-74). He hypothesized that under the influence of centrifugal and gravitational forces the individual would accept the resultant force as the true vertical. When an additional visual cue was presented, the vertical was set occasionally at a compromise position halfway between the visual vertical and the subject's body axis.[44,45]

Breuer and Kreidl (1898) rotated subjects in a centrifuge with accelerations yielding a resultant of 15 degrees to the vertical. The subjects were required to adjust the vertical to a vertical afterimage. The mean results for three subjects were 8 degrees, yielding again a compromise between the

gravitational vertical and the resultant.[6]

These early results were later confirmed by Noble (1949) and by Clark

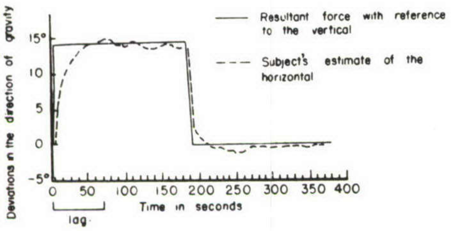

Fig. 1. Average lag of time from three subjects during visual orientation on the centrifuge at 6 r.p.m. (Computed after data by Graybiel and Brown, 1949.)

and Graybiel (1949). When an individual, who is in a stable position with respect to the vertical, is subjected to accelerations on a centrifuge, he becomes aware both of the changing direction and increasing magnitude of the resultant between centrifugal force and gravity.[53] It can be felt that the seat is tilted and that he is pressed against it with increasing force. "It is just as though the center of the earth had shifted with respect to him and the mass of the earth had increased."[12]

Similarly, the position of a luminous line seen in the dark is also subjected to a directional change determined by the resultant. When the subject faces the direction of turn and the center of rotation is at left, the luminous line seems to rotate clockwise, subsequent to the onset of rotation. In order to keep the target line subjectively horizontal, it must be rotated counterclockwise.

Under these conditions, threshold determinations were made of the apparent deviation of the line from horizontal with a variable and a constant resultant force. As mean values 2.71 degrees for acceleration and 3.37 degrees for deceleration were com-

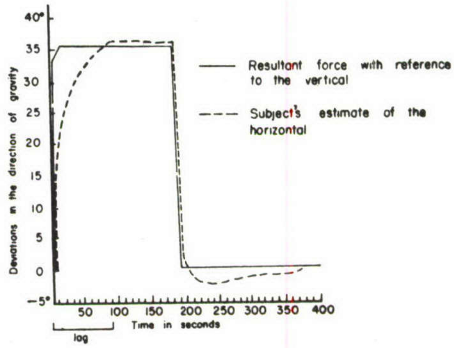

Fig. 2. Average lag of time from three subjects during visual orientation on the centrifuge at 10 r.p.m. (Computed after data by Graybiel and Brown, 1949.)

puted on several levels of stimulus intensity and duration. The general tendency of the subjects was to set the line at an angle from the horizontal which was greater than the deviation of the resultant force from gravity. No adaptation effect but a time lag before the response was observed.

The delay in visual reorientation to the resultant was measured by Graybiel and Brown (1949). The mean value of the time lag was 73.2 seconds at 6 r.p.m. and 89.1 seconds at 10 r.p.m. The mean duration for all subjects in all trials was 81 seconds. Individual differences were not great; but there is a difference at the two levels of acceleration used. The lag following deceleration was relatively short: 35.0 seconds at 6 r.p.m. and 23.3 seconds at 10 r.p.m.; and there was overshoot.[27] The mean values of the results of three subjects are displayed in Figures 1 and 2.

These curves show that during acceleration the responses to the visual sensation caused by alteration of the gravitational vertical are the more delayed, the more the new state of gravity deviates from the normal psychophysical zero-state of the individual. After the new level finally has been reached and maintained for a while, changes in the opposite direction, i.e., toward the normal state of gravity, are perceived and responded to with great promptness but with less accuracy due to an effect of overcompensation. From this we may conclude that orientation to changes in direction of resultant gravity will be either inaccurate or hampered by a considerable time delay.

Finally, Wing and Passey (1950) investigated the visual vertical under conflicting visual and acceleratory factors.[66] They report that in the absence of a visual frame of reference the resultant was accepted as vertical whether or not the body was in line with the resultant. In contradiction to Witkin (1950) who imputes dominance to the visual factors in the determination of the vertical, Wing and Passey found that in the presence of a visual frame of reference neither visual nor gravitational cues are accepted to the exclusion of the other. With increased intensity of the centrifugal force, however, the visual vertical is located relatively nearer to the vertical determined by the resultant force.

2. *Under Flying Conditions.*—It was learned by experience during flying, position orientation in the aircraft in situations of visual and gravitational conflict is problematic. Two different cases must be considered in this respect: first, accelerational forces versus direct vision of the ground and the horizon, as is the case in contact flight; and second, accelerational forces versus artificial perceptual cues, as is the case in instrument flight.

Every person who is not an experienced flyer knows the sensation of apparent tilt of the horizon and of the ground when the airplane is assuming a turn. It then seems that the positions of sky and ground have been shifted. These sensations are due to the fact that the observer incorrectly regards his environment as shifting and the direction of resultant force as fixed, rather than vice versa.

In instrument flight the pilot very often finds himself in a situation of conflict when the gravitational cues are in contradiction to the visual ones. In these situations the pilot must rely entirely on his instruments, since the information brought about by the machano-receptors by no means indicate the true position of the body and of the aircraft with respect to the ground.

The visual perception of a star-shaped target during flight when centrifugal forces are acting on the body was investigated thoroughly by Graybiel, Clark, and MacCorquodale (1946). They report the occurrence of phenomenal motion, displacement and rotation of a target during flying maneuvers including turns, bank (10 to 60 degrees), glides and dives. All displacements were observed in or close to the vertical plane whereas motion was observed not only upward

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and downward but to the right and to the left. At the onset of the bank the star was usually seen to move and to be displaced upward with a slight deflection in the direction of turn. It remained there until the plane began to recover to straight and level. The observations during and following recovery were perceptually the reverse of those observed during the banks. The target appeared to move and to be displaced downward with a slight inclination opposite to the direction of the turn, i.e., back to the true position.[28] In another study, a time lag of about five seconds in average was observed.[29]

Summing up the experimental evidence, we can assume that in situations of visual-gravitational conflict, position orientation will be made in a compromise direction between the main lines of the visual field and the resultant of the mechanical forces. In no case was the stimulation of the mechanoreceptors neglected completely when centrifugal forces were applied, nor were the main lines of visual space accepted as determinants of the orientation scheme. We may, therefore, conclude that in the opposite case when gravity becomes smaller than 1 g, disturbances of the orientational scheme may also occur, even if a visual frame of reference is secured. In transposing the human body into this new state of equilibrium, the stimulation of the mechanoreceptors, as a whole, will be altered decisively. The otoliths are known to be of importance for the orientation to the direction of gravity. When the physical characteristics of this organ are considered, one understands that if the calcareous parts of the otoliths lose their weight there will be a loss in pull and pressure on the sensory hair cells. Consequently, a stimulation of the macula will be caused which is experienced only in the situation of falling freely. Since, at the same time, other proprioceptive senses will be stimulated in a similar way, only a few somesthetic cues will act against the fall sensation.

From the foregoing, it can be assumed that the use of the eye will be of some help for overcoming the sensation of falling freely subsequent to the transposition of the individual into the gravity-free state, if a visible movement of the body relative to its surroundings does not exist; for this would be in contradiction to the fall situation experienced under normal gravitational conditions. On the other hand, we know that visual perception is apt to compromise and that a complicated mechanism of labyrinthine reflexes acts directly upon the eyes under extraordinary accelerative conditions. It was found that then the individual is not aware of the illusory nature of rotations, movements, and displacements and his environment and may take these apparent changes for granted. Furthermore, it has been demonstrated that the individual is not able to recognize illusions brought about by discrepancies between visual and gravitational cues except after a considerable lag of time. Hence, bodily disorientations as well as dislocations of objects in space, which may accompany the transition from $g=1$ to $g=<1$, will not be recognized by the subjects at all or only after a considerable and even dangerous delay.

VERTIGO AND VISUAL ILLUSIONS

In the foregoing chapter it was demonstrated that in situations of perceptual conflict illusions occur, which can give rise to disorientation in space. As far as these illusions are related to the effect of modified gravitation they will be of some importance for our subject under investigation. It is this type of illusions which also may bring forth disorientation in the gravity-free state.

Illusory effects and orientational disturbances caused by changes in gravitation, centrifugal forces, acceleration, et cetera, are often referred to as "vertigo." Under this heading we understand any sensation or feeling, which is brought about by discrepancies between subjectively experienced sensations on the one side, and objectively correct environmental facts on the other. Characteristic features in these sensations are an emotional, a psychosomatic component and a disconcerted state of mind, associated with a presentiment of danger. Vertigo and the types of mistaken perceptions akin to this phenomenon have been thoroughly studied and described by Vinacke (1946).[61-64]

Most illusory perceptions of this kind can be considered as effects of a complex of stimulation of the inner ear. The factors causing the perception as a whole cannot be separated with proper precision to identify clearly the direct stimulus-sensation relationship and the mediating sense organs. Even in laboratory tests on the centrifuge Coriolis forces generally are acting in addition on the sensory organs. However, it seems to be possible to estimate within certain limits the role of the sensory nerves for a special type of illusion. Graybiel and his co-workers (1946-1950) have studied and described two specific illusory phenomena:

1. *The oculo-gravic illusion* concerns the apparent displacement of an object in space, which may occur when the sensory receptors in the otolith organs are stimulated by a force forming a resultant vector with the force of gravity.[32] Graybiel, Clark and MacCorquodale (1946) found that this illusion occurred during flight maneuvers, when a target (luminous star) was viewed by the observer.

During climbs and glides, motion was seen in the vertical meridian. At the beginning of both maneuvers, the target seemed to move down more frequently than up. On recovery from the climb there was a marked tendency to see motion down, and from glides to see motion up. Motion was observed in fourteen out of twenty-two climbs and glides and in twenty out of twenty-one recoveries from climbs and glides.[28]

The illusory perceptions caused by centrifugal force during flight depends mainly on a stimulation of the otoliths. It was found that during the turn proper there is a direct relationship between the g-forces and the amount of displacement of the target (Fig. 3). When the gravity increased, the star moved upward and remained in the position of maximum displacement until the pilot begun the recovery. During and shortly thereafter the star was seen moving downward to the "true" position. Only in one case, the target seemed to be displaced

about 10 degrees below its initial "true" position and moved up to "true" shortly after recovery.

The vertical motion and displacement during the bank and turn were complicated by lateral motion in many trials. This involved apparent motion to the sides without displacement. Displacement was perceived predominantly upward but mostly deflected to the right or left. Motion and displacement upward may be brought forth by stimulations of the semicircular canals and of the otoliths.[30]

In another study, Clark and Graybiel (1947) report illusory motion of the target during acceleration and deceleration in flight. When the subject faced to the left, the star appeared to rotate about its central point in the direction of the resultant of the accelerating or decelerating forces and the force of gravity.[11] When the subject faced the direction of flight, no regularity in displacement of the star was observed. "On the basis of the forces involved the star could be expected to rise during acceleration and fall during deceleration" (Am. J. Ophthalmol., 32:555, 1949). The relationship between linear accelerations and apparent displacement of the visual target will be discussed later.

2. *The oculo-gyral illusion* can occur during and after stimulation of the crista ampullaris of the semicircular canals produced by angular accelerations. It is the result of nystagmus produced reflexly and consists of apparent motion and/or displacement of an object observed under these conditions.

The direction of the apparent motion is in concurrence with the sensation of rotation. If, for example, a subject is rotated to the right, a target appears to move in the same direction

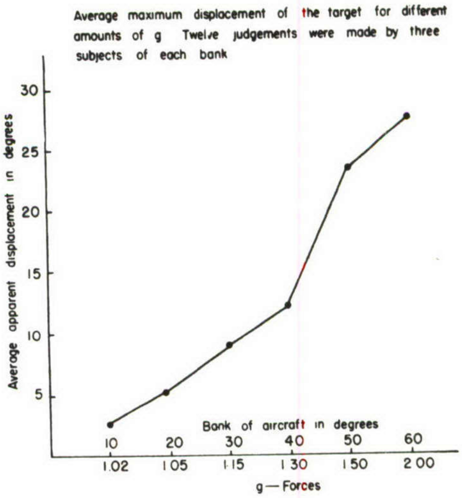

Fig. 3. Relationship between g-forces and target displacement. (Graybiel, Clark and MacCorquodale, 1946.)

with the onset of the rotation. It comes gradually to a standstill after which it may appear to move slowly to the left. With a constant rate of rotation, the target appears motionless. When the subject is suddenly stopped, the target appears to rush toward the left. This first effect is followed by a second one in which the target appears to move to the right. This second effect may persist as long as the first one or even longer. More after-effects with changing directions and fading intensities may occur.[33]

The direction of the apparent movements of induced afterimages during and following rotation is exactly opposite to that observed when a real target is fixated. Graybiel and Hupp (1945), therefore, hypothesize that

eye movements are responsible for the apparent motion. (Fig. 4).[31,32]

Stronger and more confusing illusions were obtained when a moving

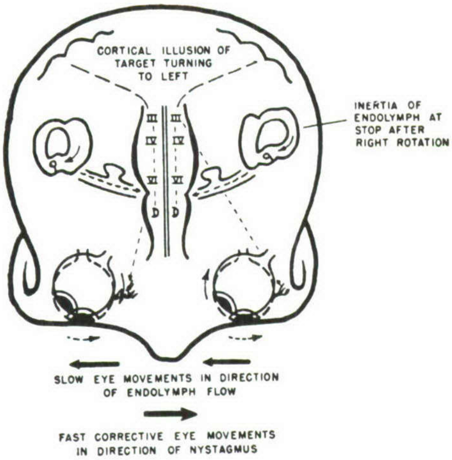

Fig. 4. Schematic diagram of the stimulation of the semicircular canals at stop after rotation to the right. The endolymph still moves to the right. The target seems to move and to be displaced in the opposite direction (direction of nystagmus). (Moffitt, Torndorf and Guild, 1948).

target was observed during angular accelerations. At first, a rapid displacement of the target in the opposite direction of turn was noticed; although, the target appeared motionless at the same time. As the target went by on successive rotations, it appeared to pass more rapidly until after approximately thirty seconds, the subject felt to be in rest while the target seemed to rotate rapidly around him. Post-rotational phenomena after deceleration were in the opposite direction and stronger.

The relationship between apparent displacement and motion was studied by Brown, Imus, Niven and Graybiel (1949). The target was observed as displaced always in the direction of the apparent motion. There were large individual differences in reports of amount and duration of apparent displacement. Correlations of independently observed nystagmus were related to both phenomena.[7]

At this point, a short recapitulation of the stimulus-sensation mechanism governing the illusory perceptions seem to be indicated. The otoliths must be considered as indicators of linear accelerations. They have a quantitative and a qualitative function because they indicate alterations of the resultant force in both intensity and direction. We further know that the discrimination of positive and negative acceleration is important for the stimulation of the otoliths only with regard to the position of the head relative to the direction of the centrifugal forces. When accelerative forces act in the direction of the horizontal (front-rear), the stimulation of the macula may be basically the same during linear acceleration and deceleration in or near the horizontal meridian. There may be brought about an essentially different sensation, however, when the otoliths are stimulated in or near the vertical meridian by forces of inertia. Since there is no doubt about the mechanical characteristics of the sensory epithel cells and their physiological functions, we can expect that in the first case they will be moved in the horizontal (back and forth); while they will be moved in the vertical meridian (up and down) in the second case. Only in the latter case definite displacements of the target above and below the "true" zero-point may appear.

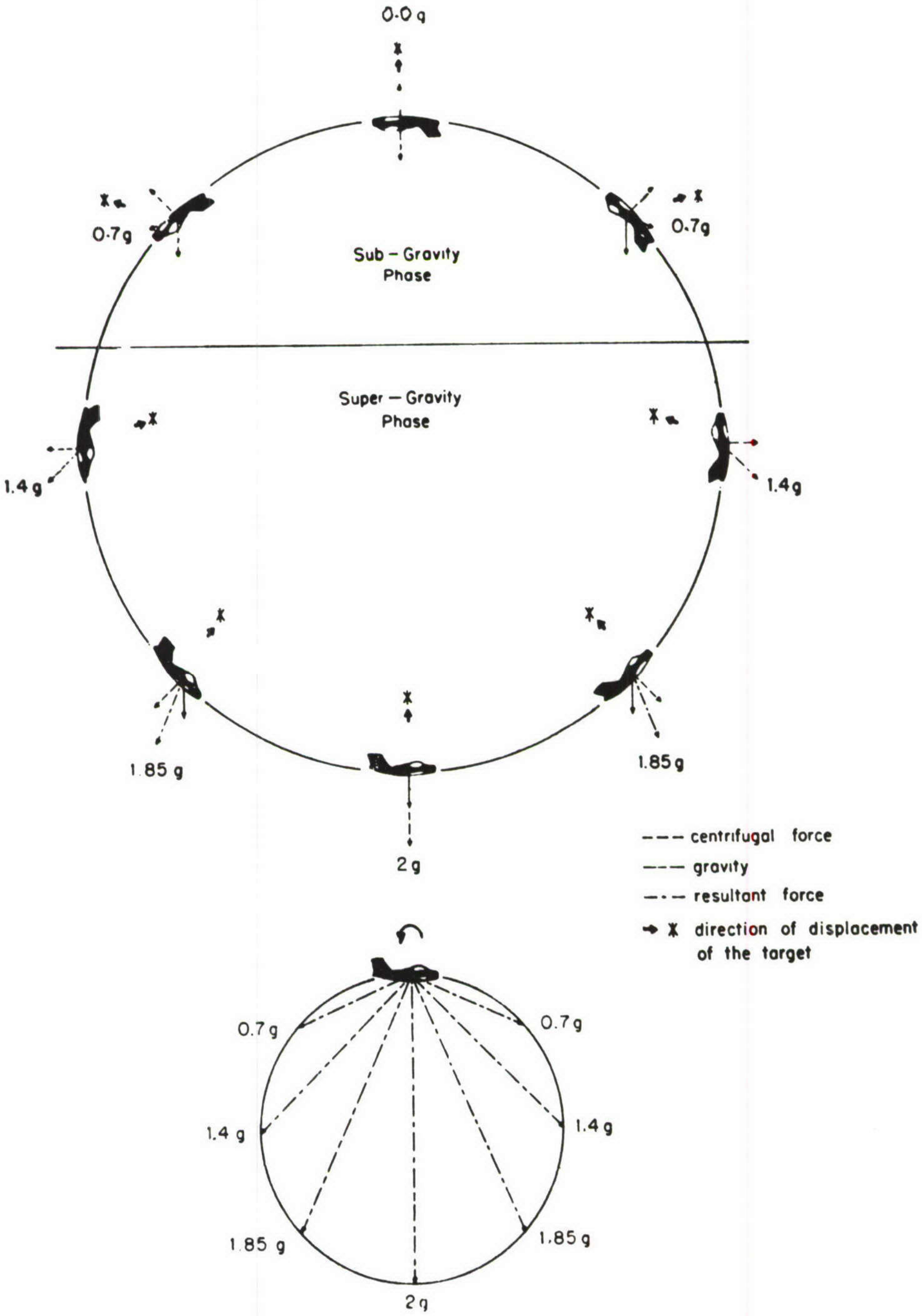

Fig. 5. Schematic diagram of the apparent displacement of the target relative to the resultant and the visual frame of reference. The aircraft is making a loop with an effective centrifugal force of 1 g.

The relationship between the labyrinth and the eye muscles is preserved in regular geometrical planes which permit the simplest of reflex arcs for adjustment of the eyes.[51] So it is obvious that motion to the right and left and displacements to the sides occur when the horizontal canal is activated by angular accelerations; and that movements and displacement up and down occur when the otoliths and the vertical canals are concerned. Graybiel's findings indicate that there was rotary motion and "rotary displacement about the central point of the star" in a clockwise direction during deceleration, and counterclockwise rotation and rotary displacement during acceleration, when the subject was facing the left. This apparent motion was probably produced by stimulations of the semicircular canals and of the otoliths, indicating the direction deviation of the resultant force in the lateral meridian of the body (Fig. 5). Furthermore, an upward deflection of the target was noted in case of inincreased g-forces during radial accelerations and a downward movement during some flight maneuvers, especially during the first parts of the dive and during recovery from the climb. There is reason to believe that during the latter maneuvers the subject was in a state of sub-gravity—a fact which Graybiel did not take into consideration. Wulfften-Palthe (1926) already described reflex movements of the eyes upward and downward during sudden climbs and dives associated with increased and decreased force. In these cases, one is not simply dealing with a change in the direction of the resultant, but in the first place with an alteration of the amount of gravity. We, therefore, expect that during transition into the zero-gravity state the individual will perceive a sudden apparent downward motion of the visual field in the direction of the feet accompanying the sensation of falling; since we also have to expect in this case reflex movements of the eyes brought forth by stimulations of the otoliths and the semicircular canals. A schematic diagram showing the displacement of the star during an ideal looping in the vertical meridian is given in Figure 5.

At any rate, sensations of falling have been observed in the aircraft during sub-gravity as well as during abnormal stimulation of the semicircular canals on the ground. During subgravity there is a feeling of weakness, especially in the legs, which may be interpreted as symptom of a sudden loss of muscle tonus, caused through the discontinuing of the normal excitation level of the otolith organs.[18] By caloric stimulations or by Coriolis forces disturbances of the equilibrium and thereby fall reactions can be produced, which are accompanied by vertigo and illusory perceptions of movement.[59]

While these sensations during subgravity and zero-gravity may occur when the individual is at rest, disturbances of visual perception must also be expected when the body finds itself in passive or active motion. Under these conditions the end organs of the semicircular canals are necessarily stimulated. These stimulations may vary depending on the posture of the head relative to the direction of the accelerating force moving the body. The oc-

currence of illusions of being rotated and a corresponding activation of the reflexes coupled with the stimulation of the vestibularis must be anticipated with certainty.

As far as adaptation to weightlessness is concerned, little conclusive can be said, since contradictory data on related problems have been reported. Clark, Graybiel and MacCorquodale (1946), Clark and MacCorquodale (1948), and Brown, Imus, Niven and Graybiel (1949) report no habituation to repeated angular accelerations and regard the Griffith hypothesis—that all of the effects of ampular stimulations are highly modifiable under repetition—as disproved.[7,13,14] Guedry, on the other side, found pronounced habituation to post-rotational stimulation by introducing visual cues.[34] Since all of them observed great individual differences in perception and habituation, it can be concluded that the perceptual pattern of the individual will not stay uniform, for it was found that at least some of the variables involved in perception do not show signs of habituation and adjustment. It was found, for instance, by Gerathewohl (1944) and by Brown, Imus, Niven and Graybiel (1949) that great differences exist between individuals as to intensity and duration of sensations of apparent motion as well as to susceptibility to perceptual disorientation.[7,24] Therefore, we may thus formulate the hypothesis that differences in adaptability to zero-gravity conditions will also exist among individuals. Since there is an adaptation to the conditions causing vertigo, a similar habituation may be possible to the state of weightlessness.

SUMMARY

The rationale of this study was an investigation of the problem, whether and how visual perception will be affected during the transition of man in the sub-gravity and zero-gravity states. Since the medical and psychological literature makes available a great deal of information on the relationship between proprioceptive and visual perception, an extrapolation to the conditions of weightlessness was made on a purely theoretical basis.

In considering the pertinent anatomical and physiological characteristics of the eye it can be concluded that reduction or entire lack of weight of the eyeball will not produce disturbing alterations of the intra-ocular pressure. As to the effect of weightlessness of the eye on the external eye muscles we may assume that slight variations in muscle balance will be compensated in a short time.

On the other hand, there is a high probability that visual perception will be affected by psycho-physiological stimulations, which will occur at least during the transition period from the normal state of stimulation (1 g) into the state of weightlessness. There is sufficient evidence through experiments on varying acceleration on the ground, on the human centrifuge, and in the aircraft indicating that visual illusions are brought about by alterations of the stimulation of the mechanoreceptors due to changes of gravity. These illusions are not recognized as inaccurate perceptions by the individual, but accepted as normal results of the prevailing effect of gravity. Incidentally, the subjective alteration of

the visual reference scheme is recognized by the individual but only after a considerable time lag.

In conventional aviation medicine the terms "positive" and "negative" acceleration are used with reference to the directional component of the vector of gravity. In order to clarify the problem under investigation, the direction and the size of acceleration and of the forces of inertia must be considered as to their effect on the stimulus-sensation mechanism. The following conclusions may be drawn by an analysis of the effects of the vector of acceleration (gravity):

1. By alterations of the subjective vector of acceleration (gravity) visual perception is markedly affected. In situations of visual-gravitational conflict, position orientation will be made in a compromise direction between the visual frame of reference and the resultant of the mechanical forces.

2. There is a direct relation between the acceleration acting on the human body and the apparent displacement of an object in space.

3. The intensity of visual illusions of this type (oculo-gravic and oculogyral illusions) depends upon the rate of acceleration and of its alterations and upon the sensitivity of the individual.

4. The direction of the subjective displacement of an object in space depends upon the direction of the acceleration. In the normal mechano-psychophysical state of the body (1 g) no sensations of force and acceleration are generally experienced and—under conditions of rest—an object in space is perceived as being at rest. When an individual, who is in a stable position with respect to the vertical, is subjected to accelerations different from 1 g, he becomes aware of the vectorial changes by both mechano-receptor and visual sensations. Under these conditions the perceived object seems to move opposite to the direction of rotation of the resultant between centrifugal force and gravity. With increasing acceleration (gravity) in the vertical direction an object or the objects within the visual field appear to be moving in an upward direction; at decreasing accelerations (in the subgravity and zero-gravity states) apparent motion and displacement of the objects in the direction down (opposite to the direction of gravity) occur.

It is very difficult to make a good guess as to the importance of these illusory perceptions for the position and direction orientation in the state of weightlessness. It was demonstrated that the pattern of mechano-receptor stimulation will be decisively changed in the gravity-free state. Normally, the mechano-receptors are adjusted to the stimulus-sensation conditions of 1 g. When flying—and especially during blind flying—the mechano-receptor stimulations can be subliminal or subpressed, while the eye can take over the control of position and direction orientation without illusory disturbances. During the transition in the gravity-free state, however, the stimulation of the mechano-receptors is changed in such a way that visual illusions will occur. This effect may be serious, since the stimulus-sensation rato is changed toward a hypersensibility of the receptors. It is obvious then that under these conditions

the ability proper of the individual to control his environment visually may be impaired.

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ATMOSPHERIC SPACE EQUIVALENCE

by

Hubertus Strughold

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Atmospheric Space Equivalence

By H. Strughold, Ph.D., M.D.

Department of Space Medicine, USAF School of Aviation Medicine, Randolph Air Force Base, Texas

IN ALL FIELDS of science, a clear definition or concept is sometimes just as valuable as a successful experiment, for both research and teaching. This is especially true in scientific fields which are apt to invite wild speculation from the outside—such as that of space flight. In this field, the concept of the functional borders between atmosphere and space, which was developed by members of the department of Space Medicine, USAF School of Aviation Medicine, Randolph Field, Texas, in 1950, has proven to be very fruitful and enlightening.

It is based upon the consideration of the various functions of the atmosphere as a whole with respect to manned rocket flight.[10] At the altitudes where these various functions cease, we meet the respective functional borders of the atmosphere. They are not found on a single topographical line at the outer limits of the atmosphere as defined by astrophysics (about 600 miles),[15] but rather at various altitude levels.

The concept of these functional borders also led to the term "aeropause" (K. Buettner).[3,4] This comprises the entire area of the atmosphere within which its functional borders are found, starting above 50,000 feet. The value of an approach of this kind lies in the fact that it clarifies the belief that in the upper atmosphere we deal with a radically different environment, compared with the familiar one encountered in the conventional flight zones including the lower part of the stratosphere.[6,19]

In this paper the term "space equivalent" will be used to denote the conditions found in the stratosphere and the upper atmosphere.[20] The applicability of this concept partially overlaps that of the functional borders of space. For the most part, however, it is broader. We can associate the term "space-equivalent" with certain levels within the atmosphere that are identical with its functional borders. Also we can apply it to the entire atmospheric region above the functional borders. Further, it can be applied to conditions which are not confined to any specific level or border—such as the zero-gravity state. And finally, because the term "equivalent" is found in many languages, it is well understood internationally. (French: équivalent à l'espace; German: Weltraum äquivalent; Italian: equivalente allo spazio; Spanish: equivalente a el espacio.)

In this broad range of applicability the concept of space-equivalence is especially apt in showing how far we have actually come toward the conquest of space. In the discussion that

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follows, emphasis will be given to those space-equivalent conditions which are physiologically of decisive importance.

Oxygen: As has been explained in several papers,[19,21] the atmospheric function of contributing to respiration ceases when air pressure drops to 87 mm Hg, because of the peculiar chemical composition of the alveolar air.[1] This is further supported by the fact that the time of useful consciousness (of man)[12] and the survival time (of animals),[7,13] after an explosive decompression to or below this air pressure, show a constant minimal value. At the corresponding altitude of 50,000 feet, therefore, we are beyond the range in which atmospheric oxygen contributes to respiration. Physiologically we have reached the zero-point in the oxygen pressure of the atmosphere, even though oxygen physically is still found there. The situation is the same as if we were surrounded by no oxygen at all, as in space. Therefore, at 50,000 feet or above, we face a space-equivalent condition physiologically with regard to oxygen.[19]

Liquid State of Body Fluids: It has been shown experimentally that the body fluids of warm-blooded animals start to boil at an air pressure of 47 mm Hg.[1] When this happens, the barometric pressure is equal to the saturated vapor pressure of body fluids at 37°C. At the corresponding altitude of 63,000 feet, then, we are beyond the range of air pressure which is necessary to keep our body fluids in the liquid state. Physiologically we have reached the zero of air pressure even though physically there is still some pressure left. It is the same as if we were surrounded by no pressure at all, as in space. Thus, at 63,000 feet and beyond, we are under space-equivalent conditions physiologically with regard to barometric pressure. For more detail, especially concerning variations, see Reference 1 and Reference 5.

Necessity of Sealed Cabin: At an altitude of about 80,000 feet we require a kind of cabin which is the prototype for future space ships or artificial satellites. This is the sealed cabin. It becomes necessary for the following reasons:

1. Technical. Due to the low air density, compressing the ambient air with present-day equipment is technically prohibitive.

2. Thermodynamic. Compressing the rarified ambient air to a physiologically useful range would produce a temperature of about 400°F in the cabin, and such temperature would be intolerable for the occupants.[14]

3. Toxicological. Ozone, and possibly other irritating chemicals, would be drawn into the cabin by an ordinary compressor at these levels of the atmosphere.

For all of these reasons, the conventional cabin, pressurized with air from outside, must be replaced by a sealed cabin, pressurized entirely from within. The need for such a cabin is itself a space-equivalent condition. For, above the level where it becomes necessary, the atmosphere is just as useless for pressurization purposes as is the vacuum of space.

The three space-equivalent conditions which we have discussed so far are caused by the loss of properties intrinsic to the atmosphere. Now let us consider some space-equivalent conditions which are the result of extraterrestrial factors originating in space itself: radiation and meteors.

In the lower regions of the atmosphere these extraterrestrial factors either are not found at all or have changed their original form by interaction with the atmosphere itself. However, at higher altitudes they approach increasingly toward the full force of their solar or cosmic origin and finally create space-equivalent conditions of their own, still within the atmosphere.

Cosmic Rays and Meteors: Most frequently discussed among these extraterrestrial factors, are the primary cosmic rays (especially their heavy components) and meteors. The upper absorption limit for the heavy primaries of cosmic radiation lies at 120,000 feet.[17] The same limit for meteors is at 400,000 feet.[11,22]

In the vicinity of the earth, however, we are protected from half the total of both kinds of matter by the bulk of the Earth itself. Under these circumstances we may better speak of *semi-space-equivalent conditions.* Other variations in their intensity should be noted. Among these is the effect of the earth's magnetic field on cosmic rays below a certain magnetic rigidity. Another is the effect of the Earth's speed on the collision energy of meteors. These effects have been discussed elsewhere.

Ultra Violet Radiation. The space-equivalent altitude for the sunburn producing ultra violet band of solar radiation (3,000 to 2,100 Å) lies above the ozonosphere at 140,000 feet.

Scattering of Visible Light. More important physiologically may be the loss of the atmosphere's power to scatter visible light, resulting in the so-called twilight or darkness of Space. This space-equivalent level is reached at about 400,000 feet.

Propagation of Sound Waves. It may be noted here that, at about this same level, propagation of sound waves becomes impossible. This silence of space is reached when the free pathway of molecules in the air becomes of the order of the wavelength of sound.[2,18]

All the space-equivalent conditions which we have discussed so far, with their variations, have one thing in common. They are found at certain topographically fixed levels of the atmosphere. Their effects would occur even in a vehicle floating freely or at rest—if such a thing were possible—at the respective altitudes where they are found. Hence, these may be called *static space-equivalent conditions.*

The Gravity Free State. One important space-equivalent condition occurs within the atmosphere, however, as a direct result of the vehicle's own movement. This is the phenomenon of weightlessness, or the gravity-free state.[8,10]

It is true that the force of gravity decreases with the inverse square of the distance from the earth's center.

At a height of 4,000 miles above the earth's surface, or twice the earth's radius above the earth's center, it is only ¼ what it is on the ground; at 8,000 miles it is only 1/9, and so on. At a distance of 36,000 miles it is reduced to a mere 1/100. The near gravity-free state at this altitude is indeed a static condition. But it could only be valid for a supported body—one lying, for example, on a tower 36,000 miles above one of the Earth's poles, if such a thing were conceivable. In practice, no one could ever experience this condition.

With a vehicle in flight, however, the situation is quite different.[9,19] Subgravity and zero gravity can then be produced at any height. The effect is produced by the motion of the vehicle itself when the force of inertia, or centrifugal force, counterbalances the gravitational force of the earth. Examples are found in certain parabolic flight maneuvers, in the orbit of an artificial satellite, or in a free fall.

In all these cases, diminished weight is a dynamic phenomenon, not a static one resulting from a topographical location. Near the earth's surface it can be produced for a few seconds. In the upper atmosphere it can be produced for several minutes. Above 120 miles where atmospheric drag is insignificant, it can be produced almost indefinitely.[16] This is the nearest feasible orbit of an artificial satellite. In space, zero gravity is the typical gravitational condition of any moving body. Since it is produced by motion, it is a *dynamic space-equivalent condition.*

No object in space is ever at rest. Perpetual motion is the normal state of the physical universe. Nor is there any point in space where the gravitational field of the earth—or of any other matter—ceases to exert some force, however small. Hence, the concept of static gravitational space-equivalence is purely theoretical, and of no significance for us.

But the concept of dynamic gravitational space equivalence, which opposes one motion and one force against another motion and another force, is of the utmost importance to us. For it demonstrates that, in flight, we may undergo an experience which is typical of space at any altitude, if only for a brief interval.

The concept of space equivalence shows us where we stand today in the advancement of flight. In the area where we encounter one or several—but not all—factors typical of space, we deal with a *partial space equivalence.* This region begins at 50,000 feet. Above 120 miles all the factors characteristic of space are met. Thus, if we ignore some minor variations, we face here a *total space equivalence* within the earth's atmosphere.

Today's manned rocket-powered craft have already advanced well into the area of partial space equivalence, passing beyond at least three important space-equivalent levels. Animal-carrying rockets have left nearly all of them behind. Unmanned two-stage rockets have penetrated deep into the region of total space equivalence. It will not be too long before piloted rockets enter that region too. Then the age of true flight in space will be before us.

SUMMARY

Within the astronomically defined extension of the atmosphere (600 mi.), conditions are found that are physiologically and/or technically equivalent to those existing in free interplanetary space. Those that occur at certain topographically fixed levels of the atmosphere are termed *static space equivalent conditions*. The levels where they begin are identical with the "functional borders" of the atmosphere. Some of these space-equivalent conditions are caused by the loss of certain vitally important atmospheric factors, which loss results in anoxia, boiling of body fluids, and the impossibility of utilizing the ambient air for pressurization of the cabin.

Other static space-equivalent conditions are the result of the appearance, in full force, of certain extraterrestrial factors such as cosmic rays, meteors, etc. These space-equivalent conditions in the vicinity of the earth are affected by the solid body of the earth, its speed, and its magnetic field.

The state of zero-gravity as it is encountered in flight within the atmosphere is defined as a *dynamic space-equivalent condition*. This condition is not associated with any height or distance from the earth. Only its permanency requires a certain level above the earth's surface.

The concept of space equivalence clearly shows us where we stand today in the advancement of flight. With regard to manned rocket-powered craft, we are in the phase of *partial space equivalence*, where one or several—but not yet all—space-equivalent conditions are encountered. Unmanned rockets have penetrated deep into the region of *total space equivalence* which for all practical purposes begins above 120 miles, if we ignore some minor variations caused by the vicinity of the earth.

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BASIC REMARKS ON THE USE OF PLANTS AS BIOLOGICAL GAS EXCHANGERS IN A CLOSED SYSTEM

by

Jack Myers

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Basic Remarks on the Use of Plants as Biological Gas Exchangers in a Closed System

By Jack Myers

Department of Zoology, University of Texas, Austin, Texas

THERE ARE two developments, imminent or foreseeable, which require means of providing for the gas exchange of human occupants of a closed chamber over fairly long periods. One of these is the atomic powered submarine; the other lies in the demands of space travel. An idea so obvious that it has occurred to many more or less independently is that such a gas exchange problem can be met by the use of a photosynthetic plant which accomplishes just the opposite gas exchange as that of the human, namely, an evolution of oxygen and uptake of carbon dioxide.[1,3] It is the same idea as the balanced aquarium, complicated only by introduction of a gaseous phase. It is an idea which suggests that we reconstruct in a small space the same balance for oxygen and carbon dioxide accomplished by the entire biological world. If this could be done completely it would, in the limiting case, duplicate the balance of the total biological world in which foods, exchanged gases, and excreta become balanced by the action of many organisms into a materially closed system driven by light energy input alone.

What may be called a *photosynthetic gas exchanger,* therefore, offers the possibility of providing for oxygen and carbon dioxide exchange as a primary objective and, as a secondary objective, may provide a part of the food requirements and disposal of excretory materials.

There is no doubt whatever that a photosynthetic gas exchanger can be devised; however, there is considerable question whether it would prove the most practicable method even with its possible secondary advantages. There are alternate competing possibilities. It is the intent of the present paper, not to attempt a decision as to the feasibility of a photosynthetic gas exchanger, but to present some of the basic considerations which bear upon such a decision. My remarks will be based upon initial work done on a current project under contract with the Air Forces.

In choice of the particular plant to be used one intuitively thinks first of the terrestrial plants which exchange their gases directly with the surrounding air. However, the higher plants are complex structures with reduced proportion of photosynthetic machinery. For this and other reasons we elect to consider first the use of algae which have the highest rates of photosynthesis found in the plant kingdom. Again, while there are many algae

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which might be used, we will base the present discussion on the green alga *Chlorella pyrenoidosa* because of our more extensive and reliable data on tensity curve attains saturation at about 500 foot-candles. There are many available experimental data from which real values can be assigned to

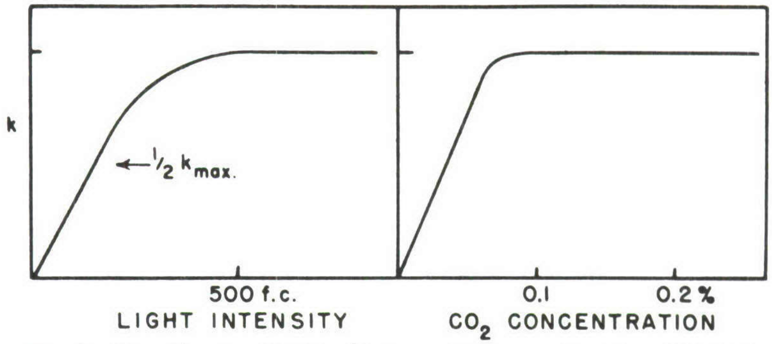

Fig. 1. Growth rate of *Chlorella pyrenoidosa* as a function of light intensity and carbon dioxide. References.[5,10]

this species. Our gas exchanger will be an illuminated tank of algal suspension aerated with the air of the sealed cabin. We will make a basic assumption that, for engineering reasons, sunlight illumination will not be feasible; artificial illumination will be provided, for example by closely spaced, glass-enclosed fluorescent tubes penetrating the tank. A cooled condenser will be necessary to reduce the humidity of the effluent air. Beyond this we shall not be concerned here with engineering considerations.

Photosynthesis and growth of Chlorella are controlled by two important conditions of light intensity and carbon dioxide concentration as shown in Figure 1. The carbon dioxide curve provides a characteristic which, depending upon the efficiency of gas exchange with the liquid suspension, should allow stabilization of the concentration in the gas phase in the range of 0.1 to 0.3 per cent. The light intensity curve attains saturation at about 500 foot-candles. There are many available experimental data from which real values can be assigned to the ordinates in Figure 1; however, most of them are based on short-time experiments. Our estimates must describe long-time, steady-state growth conditions and for a number of reasons will be generally lower than those obtained in short-time experiments.[9] The ordinate shown in Figure 1 is the specific growth rate, k, fitting the equation $dN/N = kt$ where N is some measure of cell quantity and t is time. Rates of gas exchange are necessarily proportional to k. For *Chlorella pyrenoidosa* at 25° C the maximum value of k is 2.0 per day corresponding to an increase of about 8 per cent per hour.[10] Our further discussion can be presented as a series of summary calculations based on operation at one-half maximum rate of growth.

First, what quantity of algae will be required to balance the gas exchange of one man? From Table I the conservative estimate may be made that 2.3 kilograms fresh weight of Chlo-

TABLE I. QUANTITY OF ALGAE REQUIRED FOR PHOTOSYNTHETIC GAS EXCHANGER
Estimate

Respiratory Demand per Man:	
at 120 kcal./hour (150% of BMR for 5′, 9″, 167 lb. man)	
25 liters O_2/man-hour at R.Q. 0.825	
Photosynthetic Gas Exchange for Alga Chlorella:	
Max. Rate (fresh wt. basis)	.45 1 O_2/kg.-hr.
Max. Rate during steady-state growth under light saturation	.22
Rate at ½-max. rate of growth	.11
A.Q. (CO_2/O_2) on nitrate: 0.8	
on NH_3 or urea: 0.9	
Summary Conclusion:	
2.3 kg. Chlorella = 1 man	
References.[4,8,9]	

TABLE II. AREA AND VOLUME REQUIREMENTS OF AN ALGAL GAS EXCHANGER
(Tentative Estimate)
(per man-unit = 2.3 kg. algae)

Volume Suspension:
At algal conc. 10 gm./1, requires 230 liters suspension
Layer Area:
For 1.0 cm. layer, requires area of 230,000 cm.^{2} or 240 ft.^{2}
Total Volume:
If lights, pumping, gas exchange equipment require 9 times volume of algal suspension
Total volume = 2.3 x 10^6 cc. = 80 ft.^{3}

rella will supply the gas exchange per man. It will be noted also that the CO_2/O_2 exchange quotient of the alga is such that it may be balanced against that of the human.

Secondly, what will be the area and volume requirements of the gas exchanger? The very high light absorption by Chlorella[6] and the low intensity at which light-saturation of growth is reached (cf. Fig. 1) lead to requirement of a thin illuminated layer. At wavelength 6800 AU a suspension containing 10 grams/liter will absorb 97 per cent of the incident light at a thickness of 0.4 centimeters. At other wavelengths (except in the blue) the absorption is lower. If the layer is illuminated from both sides a thickness of 1.0 centimeters is considered reasonable. As noted in Table II, the algae will have to be distributed in the gas exchanger so as to provide a rather great illuminated surface of 240 square feet for some 230 liters of suspension per man. The total volume of the exchanger then might be estimated at something like 80 cubic feet although this is entirely a problem of engineering design and the present estimate is only very tentative.

Thirdly, what will be the power requirement of the exchanger? Reliable data on efficiency of the electrical-to-light conversion and conservative estimate of the light-to-chemical photosynthetic conversion lead to calculation of an over-all efficiency of about 1.9 per cent and a power requirement of about 10 H.P. of electrical energy per man as noted in Table III. The low efficiency also gives rise to a serious problem of heat dissipation which will amount to 10 H.P. of heat per man.

TABLE III. POWER REQUIREMENTS OF AN ALGAL GAS EXCHANGER

(Tentative Estimate)

(Unit: H.P. = 640 kcal./hour)

Demand: 1 man-unit at 120 kcal./hr. = 0.19 H.P.	
Conversion, electrical to light, efficiency:	
For fluorescent lamp (highest available):	.0.19
Conversion, light to ($CO_2 \rightarrow O_2$), *efficiency:*	
Maximum observed:	.0.30-0.65
Maximum observed, steady-state growth:	.0.24
Considered reasonably obtainable:	.0.10
Over-all efficiency: 0.10 x 0.19 = 0.019	
Power Requirement: 0.19 H.P./0.019 eff. = 10 H.P./man	
References.[2,6,7]	

TABLE IV. EXPENDED AND PRODUCED MATERIALS OF AN ALGAL GAS EXCHANGER

Characteristic

Basis: 1 man unit = 2.3 kg. algae growing at ½ max. rate or 4% per hour increase—92 gm. fresh weight, or 23 gm. dry weight/hr.

Mineral salt requirement:

at ash content 5% = 1.2 gm. salt/man-hr.

Nitrogen requirement:

at 8% N = 1.8 gm. N/man-hr.

equivalent to 2.2 gm NH_3 or 3.9 gm. urea/man-hr.

References.[4,11]

Fourthly, what will be the nature and magnitude of expended and produced materials? As estimated in Table IV the exchanger per man-hour will produce 23 grams dry weight of algae of about 50 per cent protein content and will require 1.8 grams of fixed nitrogen and 1.2 grams of mineral salts. Water will have to be recycled. All human urine can be cycled through the exchanger to provide a considerable fraction of the nitrogen requirement. A fraction (as yet unknown) of the algae produced can be used by the human as food.

Many of the uncertainties in the above calculations will be removed by results of current work in a number of laboratories on the large scale culture of algae for the production of foods or specialized organic products. Certain of the problems are being examined experimentally in our laboratory. The estimates presented have been chosen conservatively and describe what probably could be accomplished if a photosynthetic gas exchanger were to be constructed today with currently available materials.

SUMMARY

Estimates of critical characteristics of a photosynthetic gas exchanger have been presented for the particular case of a suspension of the alga *Chlorella pyrenoidosa* illuminated by artificial lighting. The relatively small quantity of 2.3 kilograms of Chlorella will provide for the gas exchange of one man. Expendable materials of fixed

nitrogen and mineral salts will be required at a level of about 3.5 grams per man-hour. Both the product and the expendable materials may be reduced by recycling to an extent yet to be determined. Compact design of the gas exchanger is an engineering problem and not now estimated with any great precision; requirements of a large illuminated surface make up the principal contribution to a rather large total volume. A severe limitation arises also in the low over-all efficiency which leads to high power requirements and attendant difficulties in heat dissipation.

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COMPARATIVE STUDIES ON ANIMALS AND HUMAN SUBJECTS IN THE GRAVITY-FREE STATE

by

Siegfried S. Gerathewohl

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AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

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Comparative Studies on Animals and Human Subjects in the Gravity-free State

BY SIEGFRIED J. GERATHEWOHL, PH.D.
School of Aviation Medicine, Randolph Field, Texas

IN 1947 GAUER and H. Haber were stimulated by the fabulous advent of rocketry to make speculations about human behavior in the gravity-free state. The outlook at that time seemed to them rather dim. Since then, a lot of work has been done to clarify both the physiological and the psychological aspects of this problem. The literature has been scanned for data on previous experiences, animals have been photographed during rocket ascents and in airplanes, and experiments have been made with human subjects under sub- and zero-gravity conditions during dives and in parabolic flight. We now have much more information, both theoretical and experimental, on which to base some tentative conclusions about the behavior of man under gravity-free conditions. Nevertheless we do not believe that the problem has yet been solved entirely.

In this paper, we will limit the discussion to the psychophysiological aspects of the problem. These concern mainly the question whether the powers of orientation and sensorimotor co-ordination are disturbed under subgravitational conditions, as has been previously suggested. If this is so, flying safety would necessarily be endangered whenever subgravity states occur.

While this question is of direct application to rocket and space flight in the future, investigation of it also will yield results of a more basic nature. It is in the light of these considerations that the following presentation must be understood. Let me start with the theoretical and historical background of the subject.

In his book, "Physiology of Man in the Aircraft," Schubert[18] briefly touches the problem of subgravity. He refers to Ferry, who reported in his book, "L'aptitude à l'aviation," a weakening of the lower extremities and insecure control movements, during the gravity-free state.

According to von Beckh, Dr. von Diringshofen observed zero-gravity during flight maneuvers before World War II. He experienced about the same symptoms that Ferry did. After he became accustomed to them, von Diringshofen and his pilots enjoyed the gravity-free state as a very pleasant situation in flight.

In 1949, this author made two theoretical studies of the "Physics and Psychophysics of Weightlessness," in the first of which Dr. H. Haber participated. We suggested that during the transition from a normal gravitational state to one of subgravity, a sensation of falling may occur from

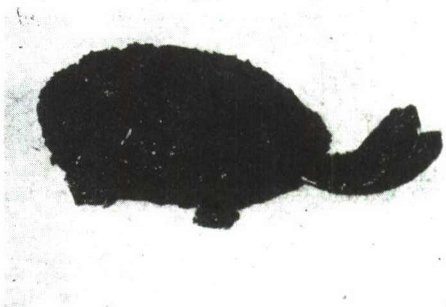
Presented at the 25th Annual Meeting of the Aero Medical Association, Washington, D. C., March 29-31, 1954.

the effect of weightlessness on the otoliths. In recent years, the functional characteristics of the otolith organs of animals have been studied by several physiologists, and the impulses travelling from these organs to the brain have also been recorded. In the absence of weight it seems plausible to expect that the messages sent to the nerve center would be contradictory and confusing, particularly since there are several otolith organs with macular layers facing in different directions. If the otoliths are weightless, will this condition produce sensory and motor disturbances? Will these disturbances be enhanced by a change in stimulation of the other mechanoreceptors under abnormal states of gravity?

Speculation about the consequences of weightlessness has been far from equivocal. While Gauer and Haber predicted impairment of muscular coordination and effects on the vegetative system including a "very severe sensation of succumbence associated with an absolute incapacity to act," Slater [19] vigorously maintained that we can do very well in space without proper stimulation of the mechanoreceptors.

We had reached this systematic juncture of the problem when the first experimental results of investigation in the gravity-free state were reported.

First, let me discuss some experiments with animals in rockets and in aircraft. Using a V-2 and two "Aerobees," Henry, Ballinger, Maher, and Simons[18] studied the behavior of several mice in sub-and zero-gravity states. They also contrasted the activity of a normal animal with that of a labyrinthectomized one. The results were reported two years ago to the Aero Medical Association. By and large, Henry and his group found that the normal mice showed violent movements and symptoms of disorientation,



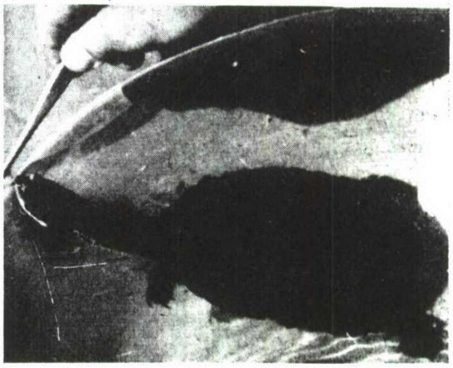


Fig. 1. *(above)*—Hydromedusa tectifera used by von Beckh in his experiments on weightlessness. The animal is on the ground searching for food.

Fig. 2 *(below)*—The test animal striking at the food which is offered by means of pincers. Under normal conditions the turtle never misses his bait.

whereas the operated animal was less susceptible to gravity-free conditions.

These findings were confirmed recently by the experiments of von Beckh[4] on water turtles (Fig. 1). Under normal gravitational conditions these animals strike like snakes at their food, projecting their S-shaped necks with pin-point accuracy toward the bait (Fig. 2). Like Henry and his coworkers, von Beckh used several nor-

mal animals and also a turtle with a permanent injury of the labyrinth. At first, this animal was severely disoriented. In striking for food, he passed over, under, or to one side of the bait. After a period of three weeks, however, the animal learned to compensate for the loss of labyrinthine cues by visual orientation. Some of von Beckh's test animals can be seen in the following slides.

Dr. von Beckh took these turtles on sub-gravity and zero-gravity dives in his airplane. Sometimes, during the transition from straight and level flight into the dive, short negative accelerations caused the water of the aquarium to rise and float freely in the air. In spite of this minor complication, von Beckh observed that only the animal with the defective vestibular organ was able to maintain his orientation. The normal animals, instead, moved very little, quite slowly, and out of balance. Since the turtles were not able to aim properly, the bait could not be caught. But in horizontal flight, all the animals acted normally. This disturbance of orientation and motor co-ordination diminished after twenty to thirty zero-gravity flights.

Experiments on human subjects were also done at that time. During the summer 1951, Scott Crossfield, NACA test pilot at Edwards AFB, produced zero- and sub-gravity states in both upright and inverted flight. Crossfield reported a sensation of "befuddlement" during the transition. This effect—probably of a psychological nature—was largely overcome after the fifth flight. He felt no sensation of falling, but he did observe a tendency to overshoot while reaching for the landing-gear switch. The most disconcerting effect was dizziness at about weightlessness on the pullout after the run.

Similar findings in jet-flight exposures to zero-gravity were reported by Ballinger[3] to the Aero Medical Association in 1952. On several of these flights, the subject would voluntarily move his head. While Coriolis effects were noted during increased gravity, no such disturbances occurred during zero-gravity, aside from a mild tendency to overreach. This tendency was then controlled by visual fixation of the target.

So long as the test subject was strapped to his seat and had strong visual references, he was able to maintain his orientation with moderate effort. However, the participants reported that "had they been unrestrained and blindfolded, disorientation might have been extreme."

This belief was confirmed by Major Charles Yeager, USAF, who made several zero-gravity flights about two years ago. He had a brief sensation of falling in the transition period, and after several seconds he noticed certain orientational disturbances. After he pulled out of the parabola, his orientation was soon restored.

Von Beckh performed a series of experiments in visual orientation and motor co-ordination on human subjects under gravity-free conditions very recently. In an aiming test, the subject had to draw crosses in seven squares arranged diagonally from the left top corner to the right bottom corner of a sheet of paper, which was placed on the instrument panel in front of him. The experiment was done in straight

and level flight, again during radial acceleration in the turn, and finally during zero-gravity, both with eyes open and with eyes closed.

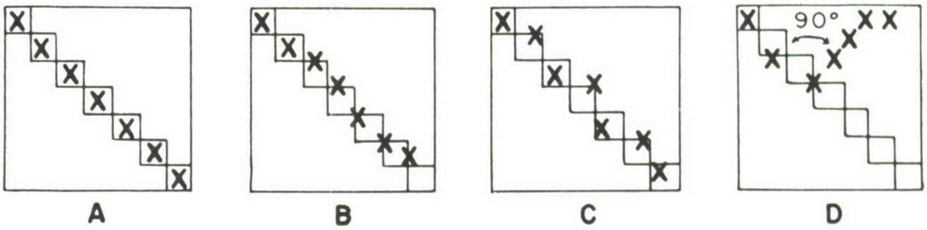


Fig. 3. Cross-drawing test. A and B were made during straight and level flight; B and C were made during the dive under sub-gravity and zero-gravity conditions. A.—eyes open: no difficulties or deviations; B.—with eyes closed some irregularities of the markings can be observed; C.—eyes open: irregularities due to sub- and zero-gravity; D.—eyes closed: a typical deviation of about 90° toward the right-hand corner occurred after the third cross was drawn.

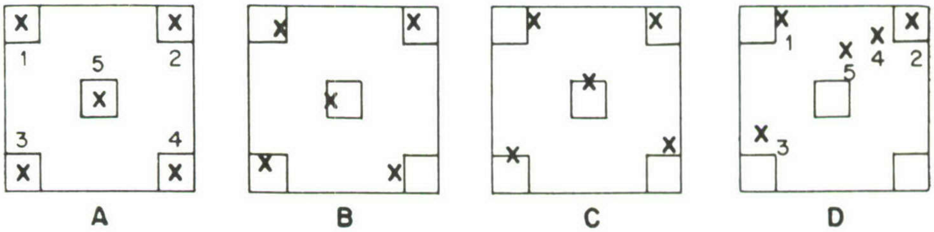


Fig. 4. Cross-drawing test used by von Beckh in his second series of experiments on muscular co-ordination in the state of weightlessness. For details see Fig. 3.

During radial acceleration, the subject had some difficulty in placing the marks in the squares. This difficulty was extreme during zero-gravity. Without visual control it was impossible to place the crosses in anything like a diagonal direction (Fig. 3).

After the third cross was drawn, a typical deviation of about 90° toward the right-hand corner was found in most cases. This was also true when another pattern was applied. The results of these tests are shown in Figure 4. A great number of flights was required, before the subjects were able to place the marks in the prescribed manner; and even then the results were never so accurate as those obtained under normal conditions.

In still another series of experiments von Beckh studied the effect of post-acceleration weightlessness. Here, the pilot produced a blackout in the pullout after the dive at about 6.5 g, and immediately afterwards flew along the ascending arc of the parabola. Under these conditions, the blackout lasted longer than after a normal pullout, and the effect on orientation was extreme during the weightless phase.

Summarizing the findings of all experiments, we can say that almost all normal animal and human subjects

have shown symptoms of disorientation and loss of motor co-ordination during the transition into weightlessness and during its early stage. The animals without labyrinthine functions were less disturbed than the normal ones in the attempt to keep their balance or to aim for food. The animals and the humans performed better, the more tactile and visual cues were provided. Henry and his co-workers interpreted this to mean that the orientational state of the animals corresponded to that of a pilot, firmly strapped to his seat, who orients himself by his instruments. It may be mentioned too, that von Beckh's experienced instrument fliers performed better in the cross-drawing test than the inexperienced ones. These are indications that it may be possible to adapt to the gravity-free state.

This last remark would seem to be the most important one, because it may free us from further troubles. Yet it must be considered very cautiously. First, we should be aware of the fact that an adaptation to the transition phase was observed so far. We still do not know what would happen if the subject had to stay in the gravity-free state for a long period of time. What we do find is a decrease of the initial disturbances of orientation in most cases.

Light is also shed upon this problem by some electrophysiological studies. Experiments of this kind made by Adrian[1] and by Lowenstein,[17] with nervous stimulation of the otoliths of the cat and of the Thornback Ray-fish (Raja clavata), had shown that the frequency of nerve impulses sent to the brain depends upon the position of the head, and therefore upon the vector of gravity. There is some experimental evidence that, after the cessation of weight, the otolith organs

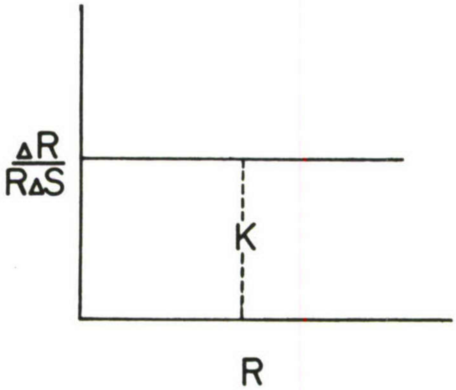


Fig. 5. Schematic representation of Weber's belief: $\frac{\Delta R}{R \Delta S} = K$. R = a measure of the "stimulus," usually expressed in absolute (c.-g.-s.) units; ΔR is a necessary change of stimulus to produce a just noticeable difference ΔS in sensation (Modified after Holway and Pratt 1936).

will settle down at a "basic" pulse frequency which is characteristic of weightlessness. This frequency will be altered by linear acceleration, for instance, through voluntary head movements. In summing up Adrian's and Lowenstein's results, Slater[19] concluded that "if a particular nerve always transmits some impulses, whatever the position of the head, then the nerve endings are always being stimulated to some extent, in whichever direction the otoliths are pulling. Such a nerve, therefore, is stimulated even when the otoliths are pulling towards the macula, but that stimulus should be absent when gravitational pull is absent, in which case no false messages will be sent to the brain." In

this case, the subject would soon learn to interpret the absence of nerve impulses correctly.

There is still another problem which must be mentioned in this connection: enough, though, no such disturbances were observed when the subjects moved their heads during zero-gravity. This finding suggests several alternative possibilities.

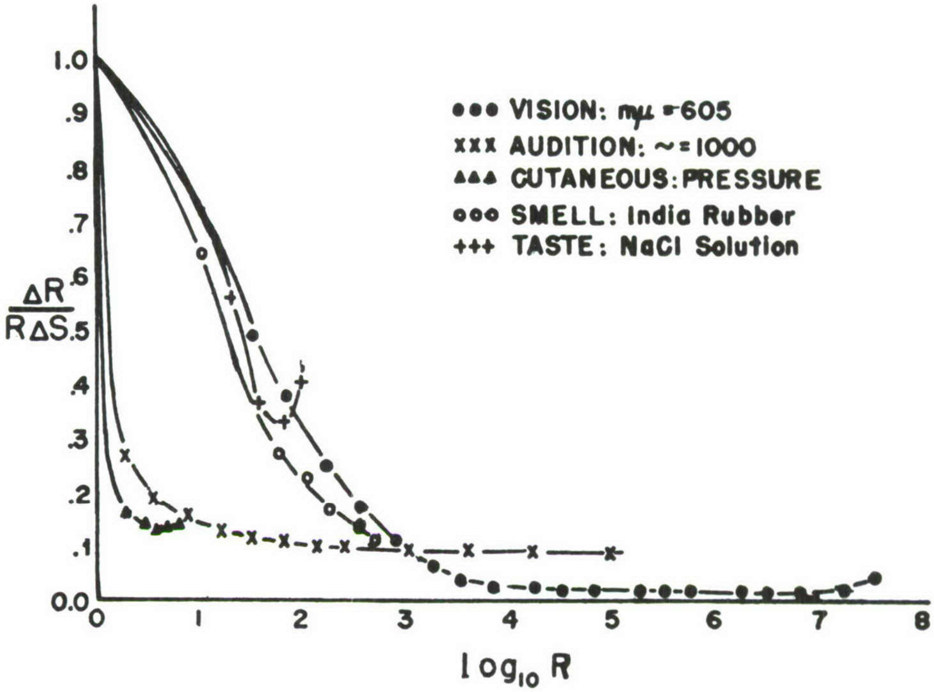


Fig. 6. Weber-Fechner functions representing five different sense modalities. Weber-ratios shown as functions of the logarithm of the stimulus. Except for the rise after passing through their minima the curves can be approximated by the function $\frac{\Delta R}{R\Delta S} = \frac{1}{b}\left(\frac{1+a}{R}\right)$ rather than by the function given in Fig. 5. (Modified after Holway and Pratt 1936.)

namely, the aggravation of vestibularly-produced disturbances according to the Weber-Fechner law, predicted by Gauer[9] in 1950.

It is a well-known fact that orientational disturbances occur through additional acceleration—the so-called Coriolis-forces—during increased weight. Ballinger's test subjects noted this effect in their flights. Strangely

The first is that the otolith organs do not furnish direct information about position and gravity, but only affect our sense of equilibrium indirectly, by control of the balancing muscles and of the eyes (Slater).[19] The Coriolis effects during increased weight may then be caused solely by endolymph movements in the semicircular canals. At any rate, what we

know is that the disturbances are caused by the *additional* acceleration. We cannot expect any Coriolis forces to be produced by head movements,

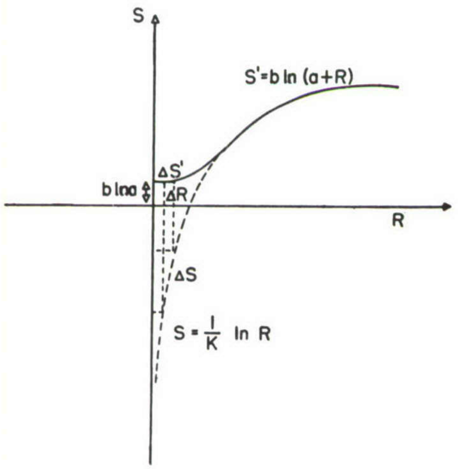


Fig. 7. Schematic representation of modified and unmodified Weber-Fechner function. According to the unmodified form of the Weber-Fechner function, strong sensations are caused by minute changes of stimulation in the region of small stimuli. According to the modified form only a small change of sensation is produced under the same conditions.

however, when the system is at rest. This conclusion would in turn mean that the vestibular system is not stimulated by the loss of weight alone; or at least it is not excited in such a fashion that acceleration produced by voluntary movements would have a confusing effect.

Secondly, we may argue that the application of the Weber-Fechner law is not appropriate to demonstrate the relationship of stimulus to sensation in the gravity-free state (Fig. 5). While it is not my intention to discuss the limitations of this psychophysiological law here, I should remark that it is far from being universal. The exceptions to it are neither negligibly small nor are they unimportant. It has been shown by numerous investigators that the assumption of a constant fraction of the stimulus magnitude in each barely noticeable difference of perception is merely an approximate statement of a special case, and that Fechner's logarithmic formulation does not represent the true relationship between the intensity of the stimulus and the magnitude of sensation over the whole range of perception. Figure 6 shows the data from experiments on threshold discrimination of various senses. If we plot the general mathematical function expressing these stimulus-sensation ratios, we usually obtain an S-shaped curve. Such a curve has an approximately linear region at about the inflection point near the center, when the scale of intensity is extended in both directions, as shown in Figure 7. Furthermore, the Weber-Fechner law expresses the relation of the scales only if there is homogeneity between the two series of magnitudes. The question in our case is: what properties can be associated with both stimulus and sensation magnitudes? One might think of units associated with the activity of nerve discharge, as demonstrated by Adrian. But we cannot definitely settle this question, and we think it is very hard to measure. So there is much doubt as to the stimulus-sensation ratio, and as to the interpretation of results of that kind.

Finally, von Beckh's experiments on post-acceleration weightlessness yielded strong effects of disorientation. Even the sensation of inverted flight was noted shortly after the beginning

of the gravity-free state. We may hypothesize that this effect was the result of an enhanced "contrast" between increased acceleration and weightlessness thereafter; but we still cannot explain the sensation of flying upside down connected with it.

This survey of the work done on the investigation of weightlessness, and the progress made on it during five years of research in this field of space medicine, is by no means exhaustive. There are other problems which have not been treated here, and which must be investigated before we understand definitely the stimulus-sensation mechanism, the process of adaptation, the tolerance-differences between individuals, and other problems of the gravity-free state. Slater proposed the investigation of nerve discharges from the otolith organs during weightlessness. Von Beckh suggested that we study the otolith reactions in zero-gravity with various positions of the head. We are also planning to investigate the eye movements and visual illusions during the transition into the weightless state. Not only because of its scientific value, but also because of its practical application for space flight, the exploration of human behavior under gravity-free conditions should be considered as an important goal.

ACKNOWLEDGMENT

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MAN'S MILIEU IN SPACE (A SUMMARY OF THE PHYSIOLOGIC REQUIREMENTS OF MAN IN A SEALED CABIN)

by

Richard M. Fenno

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Man's Milieu in Space

A Summary of the Physiologic Requirements of Man in a Sealed Cabin

By Major Richard M. Fenno, USAF (MC)

IN AN AGE of high altitude and high performance aircraft, it is necessary to develop a method for designing and constructing sealed cabins for flights beyond the atmosphere of the earth. This subject is of interest since it is apparent that, strictly from an engineering standpoint, it is now possible to build craft which can travel at great heights and at high velocities. The problem is now that of providing a safe and comfortable gaseous environment for the human occupants. Such a physiological environment can be provided above 70,000-80,000 feet altitude only by an isolated, self-sustaining capsule; a true sealed cabin.

The term pressurized cabin refers to those cabins in which the atmospheric pressure is maintained and the cabin ventilated by superchargers or compressors. This is not a serious problem for commercial aircraft which rarely fly at extreme altitudes. But for very high flying military aircraft, pressurized cabins become a practical impossibility, for at 100,000 feet altitude the cabin pressure/ambient pressure ratio would be approximately 65 to 1 with an interior pressure of 10 psi (corresponding to a cabin altitude of 10,000 feet). The exit temperature of air compressed to 10 psi at 100,000 feet altitude from a compressor capable of such a prodigious feat would be of the order of 1000° F. At this altitude 6.5 horsepower are required to compress one pound of ambient air to 10 psi, a power output that is far beyond the practical capacity of present-day compressors, not to mention the problem of dissipating the heat produced.[11]

Furthermore, an aircraft equipped with a sealed cabin can fly with safety through such hazards as toxic and radioactive clouds since no outside air reaches the occupants of such a cabin. Were an aircraft flying above 80,000 feet equipped with a compressor capable of pressurizing its cabin to a comfortable atmosphere for human occupants, its cabin probably would contain toxic amounts of ozone. Pressurized cabins then, are of limited usefulness by reason of low atmospheric pressure and the presence of ozone at high altitudes.

In the following paragraphs a critical review of the available information on this subject will be presented as compiled in the Department of Space Medicine, USAF School of Aviation Medicine, Randolph Air Force Base, Texas. Its purpose is to help provide an up-to-date source of information which can be used for further research.

From the Department of Space Medicine, USAF School of Aviation Medicine, Randolph Air Force Base, Texas, with the technical and editorial assistance of H. Strughold, M.D., and H. G. Clamann, M.D., Department of Aviation Physiology.

Major Fenno is now associated with the Johns Hopkins School of Hygiene and Public Health, Baltimore, Maryland.

HISTORICAL

Until recent years, little thought has been given to the engineering details of sealed cabins for stratosphere and space flight.[2] Probably the idea originated in Science Fiction writings, or rather in the minds of Science Fiction readers. Early authors in that field of fantasy, glibly sidestepped the problem of artificial atmospheres in space ships. However, at the first symposium on Space Medicine, organized by General Harry G. Armstrong at the USAF School of Aviation Medicine in 1948, the problem of O_2 storage for space flight, among other things, was touched upon for the first time from a strictly scientific viewpoint.[4]

The most valuable information on cabin acclimatization to date has come from balloon ascensions. In March 1933, Auguste Piccard published the results of his ascensions in a sealed gondola.[14] The first flight, in 1932, was deemed a failure because of severe discomfort to the occupants of the gondola. Prior to the flight, while inflating the balloon, the gondola was dragged from its cradle, causing damage to the rotating apparatus. The black portion of the gondola faced the sun throughout the flight, causing the interior temperature to rise to 104° F. Furthermore, the valving apparatus failed and the balloon descended only after nightfall when the gas in the balloon had cooled sufficiently to lose lift.

Only a very short description of the oxygen supply and CO_2 and H_2O absorption apparatus was given by Piccard. Liquid O_2 was used and the CO_2 was absorbed by alkali.

Stevens and Anderson in 1934 and 1935 made two historical balloon flights, the first of which nearly ended in disaster when the hydrogen in the balloon exploded.[18]

TABLE I. AIR CONDITIONING DATA—EXPLORER II

	Pounds
Oxygen consumed	1.71
Oxygen evaporated	14.60
Oxygen carried	41.60
Nitrogen evaporated	17.00
CO_2 given off by occupants	1.99
H_2O in gondola at time of closing ports	.04
H_2O in gondola at time of opening ports	.02
H_2O given off by occupants	2.80
Maximum H_2O removal by 15.25 pounds of NaOH	3.20

The second flight, in the *Explorer II,* in which helium was used, was a smashing success. The record altitude of 72,395 feet was reached and much valuable data obtained relative to atmospheric conditions at high altitude. These data were published by the National Geographic Society[19] and medically evaluated by Armstrong.[3].

The gondola was constructed of Dowmetal, a light magnesium alloy. After the hatches were sealed at an altitude of 16,000 feet, O_2 was supplied from a mixture of 45 per cent liquid O_2 and 55 per cent liquid N_2 in a vented container. The liquid was forced through a vaporizing coil placed at the top of a column containing the CO_2 and H_2O absorption apparatus. A fan forced continuous circulation of the gondola air through this vaporizing coil and thence through the CO_2 and water absorbing column which contained 15.25 pounds of sodium hydroxide (NaOH) pellets in twelve cotton gauze bags. Cabin altitude was maintained at about 13,000 feet by an automatic siphon type valve. Table I shows the pertinent

TABLE II. AVERAGE O_2 CONSUMPTION AT VARIOUS LEVELS OF ACTIVITY
(cubic feet/hour)

Rest	0.5
Moderate exercise (walking 3 mph)	2.26
Strenuous exercise (walking 5 mph)	5.40

data on CO_2 and H_2O absorption and O_2 consumption by the two persons in the gondola.

The interior of the gondola was quite comfortable throughout the 5.75 hours during which the hatches were sealed The rotating mechanism, consisting of an electric fan on a steel arm worked perfectly even in the rarified atmosphere, and the temperature inside the gondola rose from 21 degrees F. at the start to 43 degrees F. at the ceiling although the outside temperature fell to —81 degrees F. at 68,000 feet.

The atmosphere within the gondola was quite comfortable. However, the use of NaOH as both a CO_2 and H_2O absorber was not recommended due to the narrow margin between the amount of H_2O actually absorbed and the amount which would have saturated the NaOH (Table I).

Experiments are currently being conducted at Hollomann AFB, New Mexico, with animals in aluminum cannisters in an effort to provide a livable sealed cabin atmosphere for high altitude studies of cosmic ray effects. To date more than a dozen balloon flights have been made by the Aeromedical Field Laboratory at Hollomann and work has been done by General Mills, Inc., the Lovelace Foundation, various engineering companies, and others, in the quest for a satisfactory method. Animals have been recovered alive after ascents in excess of 90,000 feet.[17]

The Aerobee Rocket flights with monkeys and mice, heralded as milestones in the conquest of space, did not contribute significantly to the solution of sealed cabin problems since the flights were so short that it is possible the animals could have survived on the oxygen in the cabin alone.[8]

PHYSIOLOGIC REQUIREMENTS OF MAN IN A SEALED CABIN

Since it is mainly within the province of the engineers to construct a shell which can maintain a comfortable range of heat exchange and resist high pressure differentials, little attention will be paid to construction details except in a general way. An air-conditioning survey has been conducted by the Harper Engineering Company outlining requirements for a specific type of high altitude research vehicle.[1]

In general, the physiologic requirements are as follows:

A. *Oxygen Requirements.*—As seen in the data of *Explorer II* (Table I), nearly forty times as much O_2 was carried as was actually consumed by Stevens and Anderson in a 5.75 hour flight. Roughly one-third of the O_2 carried was vented in order to maintain a steady cabin altitude. Only 1.71 pounds of liquid O_2 were consumed by two adult men performing moderate exertion in a confined space. This suggests that if venting can be held to a minimum, O_2 supply will not be too difficult a problem. Table II shows average oxygen consumption at several levels of activity. These may be lowered somewhat by a prolonged gravity free state.

TABLE III. ESTIMATION OF CO_2 PRODUCTION, WEIGHT OF ALKALI CANNISTERS NEEDED FOR CO_2 ABSORPTION FOR VARIOUS PERIODS OF SUBMERGENCE ON A GERMAN FLEET-TYPE SUBMARINE CREW, 50 MEN*[16]

After	1	4	8	12	16	Hours
Total CO_2 produced; liters	1050	4200	8400	12,600	16,800	
CO_2 Content, percent	0.21	0.84	1.68	2.52	3.36	
No. Cannisters needed for total absorption of CO_2		10.5	21	31.5	42	per day
		525	1050	1575	2100	for 50 days
Weight of Cannisters in Kg.		26.25	52.5	78.75	105	per day
		1312.5	2625	3937.5	5250	for 50 days

*German U-boats during World War II were normally supplied with 800 such cannisters.

The problem of weight is an important one if long flights are to be considered. Even in submarines, where storage space is at a premium, it is necessary for the crews to be subjected to long periods of oxygen depletion, necessitated by the ever-increasing ability of these craft to remain submerged.[9] Clearly, an efficient CO_2 and H_2O absorbing apparatus is necessary for long flights in order to conserve supplies. A fiberglass oxygen container now under development should alleviate the weight problems in aircraft considerably. An experimental model has the same weight as a standard USAF D-2 oxygen bottle (5 lbs. when full) but holds five times its capacity of oxygen under a pressure of 5,000 psi.* The capacity of the D-2 bottle represents 221 liters of oxygen at standard temperature and pressure. Liquid oxygen would be most economical if a container of sufficient strength to contain it without venting were available.

B. *Carbon Dioxide*.—(CO_2) and water (H_2O) elimination.

There are four basic methods of CO_2 removal:

1. *Chemical*.—Several excellent chemical methods of CO_2 absorption have been used which are satisfactory for flights of less than thirty hours' duration.[1] Sodium hydroxide (NaOH) was found satisfactory by Stevens and Anderson for CO_2 removal, but not for H_2O removal due to the small safety factor.[19] Magnesium Perchlorate ($Mg(ClO_4)_2$) was found to be satisfactory by the Harper Engineering Company.[1] Others are soda lime (a mixture of calcium and sodium hydroxides), lithium hydroxide (LiOH) and other alkalies. The disadvantage of chemical absorbers is that they all have a limit of saturation and the cabin continues to carry with it all the H_2O and CO_2 that has been absorbed from its atmosphere, while the efficiency of the absorber continues to decline. Table III represents a calculation of the number of alkali cannisters, and their combined weight, necessary to remove the CO_2 from a submarine with an air volume of 500 cubic meters and a crew of 50 men. By interpolation it is seen that for a crew of five men in continuous flight for seventy-two hours, 18.9 of these cannisters with a weight of more than 100 pounds would be needed.[16] However, most chemical absorbers can be induced to part with their H_2O and CO_2 rather easily and a method may be developed of heating to drive off H_2O and CO_2 and release of same through an airlock without loss of oxygen.

Table III also shows an increase in CO_2 content to 3.36 per cent after sixteen hours of continuous operation. Studies of the composition of the atmosphere in submarines have shown that after prolonged submerged operation the CO_2 content may reach 5-6 per cent while the oxygen drops to as low as 15-17 per cent.[16] Under these conditions the combined effects of hypoxia

*Simons, Major David G.: Personal communication.

and CO_2 accumulation are additive and may result in depression, headache, disorientation and loss of judgment and efficiency. These conditions appear even in snorkel equipped vessels. It is essential that the CO_2 content of a sealed cabin atmosphere be kept well below 3 per cent.

2. *Physical Methods*

(a) The "water scrubber." A method of washing out CO_2 with sea water. It is said to work well in submarines.

(b) Filters. The basic principle is selective permeability, e.g., a thin rubber dam is more permeable to CO_2 than to O_2.

(c) Venting. Controlled venting would be a simple solution for flights of short duration. It would be wasteful of O_2 supplies on a long flight, however, and probably of limited usefulness for this reason.

3. *Air reduction-liquefaction.*—Essentially a distillation method of CO_2 removal. Liquid CO_2 could then be jettisoned. This type of apparatus is at present heavy and bulky.

4. *Enzyme systems.*—Theoretically, carbonic anhydrase could be made to remove CO_2 which could then be compressed or liquefied and jettisoned.

Experiments are being conducted with plants to determine if photosynthesis can be utilized. J. Meyers, on the basis of preliminary work with algae, indicates that not only may the oxygen requirement be met, but the CO_2 removed as well, while providing part of the food requirements.[18] This is widely done in balanced aquaria, why not in sealed cabins? Unfortunately, the efficiency of a photosynthetic gas exchange system is low. Myers estimates that for a 167-lb. man at 120 Kg calories per hour (150 per cent of normal BMR), 25 liters of O_2 at an R.Q. of 0.825, would be required and could be supplied by 2.3 kilograms (fresh weight) of Chlorella pyrenoidosa, a species of green alga.[13] This does not seem unreasonable until the requirements of this plant are examined. A suspension of 10 grams/liter provides maximum absorption (98 per cent) of light at 6800 AU in a layer not more than 1.0 centimeter thick if illuminated from both sides. This requires an illuminated surface of 240 square feet for 230 liters of suspension per man. Based upon the efficiency of fluorescent lamps (the highest obtainable) at 19 per cent and the $CO_2 \rightarrow O_2$ efficiency of the alga at 10 per cent, 10 horsepower would be required to produce one "man-unit" or 130 Kg. Cal O_2 equivalent per hour. This is a rather impractical power requirement. Moreover, this type of machinery would require about 80 cubic feet of space per man-unit.

However, in view of its very newness, and the high probability that more efficient photosynthetic gas exchangers may be developed, this line of research should not be abandoned as long as the prospect of new and improved power, as well as light sources, exists. N. J. Bowman has suggested the use of algae for food and atmosphere control on long flights but recommends the lighter and less complicated oxygen storage method with chemical CO_2 removal and storage of dehydrated food for shorter flights.[6]

C. *Temperature.* — Early thought along this line was concerned with keeping warm since the temperature at 70,000 feet can be as low as —80 degrees F. Indeed, it has been, and still is, a large factor in aviation today.

However, with increasing speed of aircraft exceeding Mach 2, high skin temperatures and hence high cabin temperatures are being encountered. This will become an increasing problem as speeds increase within the earth's atmosphere with current thought being directed toward refrigerated cabins, and ventilated pressure suits.

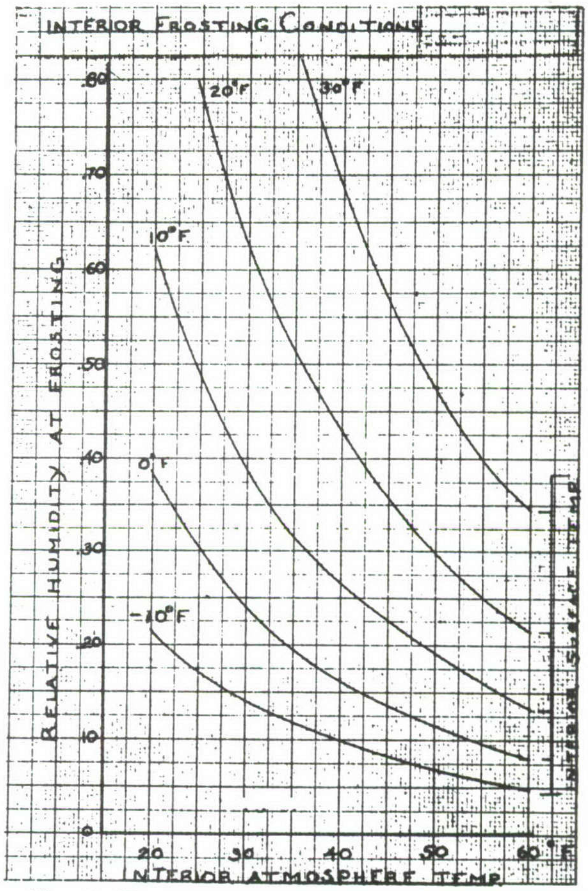

Fig. 1. Temperature and humidity factors in hull frosting.

Space, on the other hand, cannot be truly said to have any temperature at all, since there is no atmosphere (except for some widely dispersed gas clouds) to conduct and absorb heat. The problem, then, is essentially one of reflection-absorption of radiant heat; the dark body absorbs and the light body reflects. A properly controlled balance between reflectors and absorbers is necessary for the cabin in flight outside of the atmosphere.

The comfortable range for human occupants of a sealed cabin is 50-75 degrees F. However, frosting of hull and windows occurs with an interior temperature of 50 degrees F., a rela-

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tive humidity of 47 per cent (comfortable humidity range 40-60 per cent), and an interior surface temperature of 30 degrees F.[1] According to these findings the lowest possible interior temperature and lowest possible humidity consistent with comfort should be maintained since the lower the temperature, the higher the humidity can be without frosting. (Fig. 1).

Conversely, with an interior atmospheric temperature of 60 degrees F., and internal hull temperature of 30 degrees F., frosting will occur at 35 per cent humidity according to the Harper Engineering Company. Clearly, in order to maintain a comfortable range of atmospheric temperature, the internal hull temperature should be higher than 30 degrees F., if frosting is to be prevented. Moreover, an individual surrounded by an atmospheric temperature within the "comfort

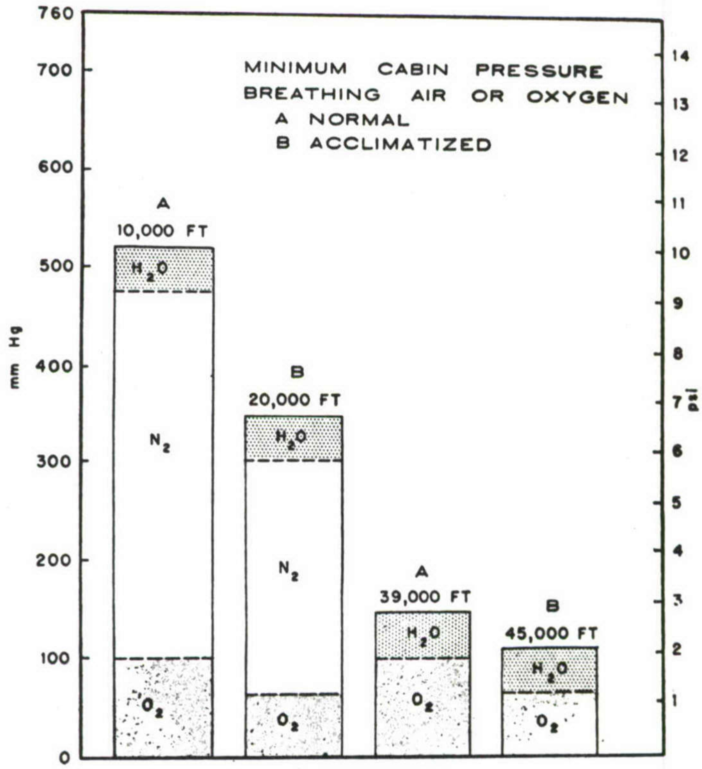

Fig. 2. Safe limits in cabin pressure when breathing air or breathing oxygen for normal individual (A) and for crews who have been specially adapted to low barometric pressure by natural acclimatization (B). The columns are based upon the partial pressure of gases for inspired air saturated with water vapor at body temperature. Copyright 1952, The Lovelace Foundation.

zone" could lose large amounts of body heat by radiation toward a cold wall with resultant discomfort and danger to health.

In actual space flight, except for periods of acceleration and deceleration, a condition of zero G or gravity free state will prevail. This will almost certainly bring heat exchange by convection to a standstill. A human being would be surrounded by an atmosphere of his own expiratory gases—a condition which, though not dangerous, could be quite uncomfortable. During sleep there might be danger of suffocation as well as overheating. Forced circulation of the cabin atmosphere then will be necessary during any period of zero G, either by fans or by artificial gravity induced by rotation of the cabin or by continuous acceleration.

D. *Pressure.*—The ideal atmospheric pressure is, of course, that pressure at or near sea level. But this would exert a pressure of more than 2,000 pounds per square foot on the interior of a hull in space. Comfortable cabin pressure would vary with the amount of O_2 present. Probably the lowest safe cabin pressure is that equivalent to not more than 30,000 feet altitude if the cabin air were 100 per cent O_2 This would exert a hull pressure of only 628 pounds per square foot. Clearly, the lower the inside pressure, the lighter the hull can be. On the other hand, long exposure to 100 per cent O_2 at higher

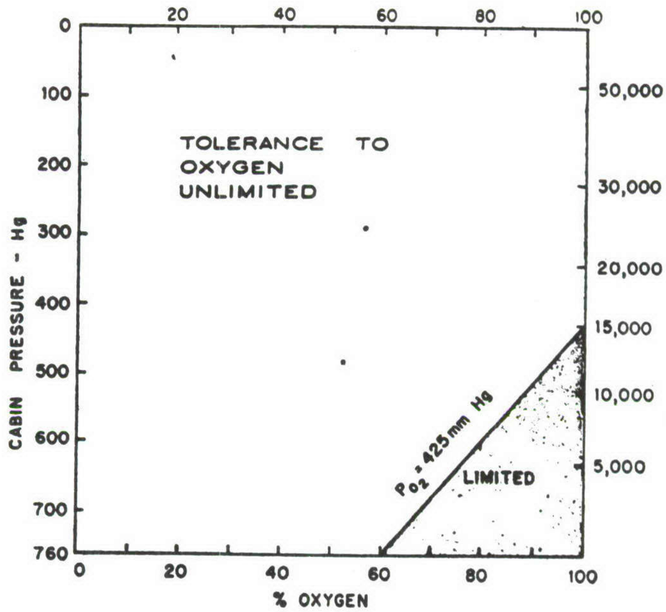

Fig. 3. Tolerance to oxygen as related to total pressure and oxygen content in a pressure cabin. At partial pressures of O_2 in excess of 425 mm Hg. toxic effects may ensue, depending on time of exposure. Copyright 1952, The Lovelace Foundation.

pressure causes irritation of the lungs and eventually pulmonary congestion and edema. Probably the space ship of the future will have less weight restriction than is imposed by present fuels, allowing for stronger hulls and higher interior pressures. The lower limit of comfortable oxygen partial pressure is about 90 mm Hg. CO_2 should not exceed 10 mm Hg. These limits can be reduced slightly by acclimatization[10] (Fig. 2). According to Clamann and Luft, tolerance to oxygen is limited only if its partial pressure exceeds 425 mm Hg. This means that an atmosphere of pure oxygen is safe if its equivalent altitude is above 15,000 feet.[10] (Fig. 3).

E. *Noxious Gases.* — Armstrong doubts that odors can be controlled.[12]

Although noxious gases such as carbon monoxide and exhaust fumes can and must be held within safe limits, the removal of cooking odors, body odors and the like, while not essential to life, certainly effect comfort and morale. It is not inconceivable that foul odors can be a danger to life if they result in severe nausea, vomiting and concomitant loss of crew effectiveness.

Satisfactory methods of odor masking are in use throughout the civilized world. Most of these, however, depend upon displacing of one odor with another and subsequent dispersal into that vast diluent, the atmosphere.[7] This is manifestly impossible in the limited atmosphere of a sealed cabin. Toxic materials such as exhaust fumes, fuel and hydraulic fluid vapors can be excluded from the cabin by engineering means. But such normal physiologic excreta as methane, hydrogen sulfide, indol, skatole and the excretory amines are very much with us, and when they cannot be removed by dilution and dispersion, other means must be employed. Even the commonplace odor of acrolein, produced from overheating of cooking fats can give way to toxic concentrations in a confined space—an occupational hazard of chefs. Smoking, ordinarily a benign habit, could produce dangerous amounts of carbon monoxide over a prolonged period of time. Suggested by H. Specht are absorption of many of these substances by the same alkali which removes CO_2 and water and, more important, continued research for specific methods of removing those which must be considered hazardous during prolonged exposure.[18] Activated carbon filters are effective for many substances. Toxicity data for individual compounds and time-concentration curves have been outlined by the Committee on Aviation Toxicology, Aeromedical Association.[5]

F. *Noise.*—Flight above the atmosphere is probably noiseless. However, although jet aircraft are said to be almost noiseless, the sound level in a jet cockpit in flight is of the order of 117 DB.[2] Engine noise cannot be entirely eliminated, but overall noise level should be below 70 DB[12] for comfort, lessening of fatigue, and prevention of acoustic trauma.

G. *Radiation.*—Research in this sphere belongs more properly to the physicist and engineer but must be considered by the Flight Surgeon along with safe limits of other factors.

According to C. A. Tobias,[21] even extensive high altitude flying presents only a small hazard from cosmic and other radiation. He estimates that a pilot flying 1,000 hours a year at 55,000 feet receives about 16 MR per week, clearly a safe dosage. How much this dosage would be increased above the ionization layers of the atmosphere is not known. Some shielding is apparently necessary for space flight, although it is possible that cosmic radiation above the ionization layer of the atmosphere may be entirely innocuous to living tissue.[22] It is presumed by some workers[21] that dosage above the atmosphere may approach or exceed the 0.3 REM per week now considered permissible. H. J. Schaefer theorizes that large increases will be met with at very high altitude due to the removal of the shadow effect of the Earth and the absorbing qualities of objects of large mass (aircraft).[15] The latter is significant because the hull of an aircraft might induce dangerous ionizing radiation through collision of high speed particles which might otherwise pass through the body without causing significant damage.

DISCUSSIONS AND RECOMMENDATIONS

It is clear at this time that more work should be done on all phases of sealed cabin acclimatization, a need which daily becomes more apparent.

Since man's environment — his Milieu in Space—must be controlled within rather narrow limits, it is apparent that the engineering aspects of sealed cabin acclimatization have been neglected, while the experts worked with fuels, engines, metals, and control systems. This writer is of the firm opinion that judgment and perspective thinking can never be built into a machine, therefore, man must go aloft and see, and learn for himself.

It is recommended that pressurization of very high altitude aircraft cabins by superchargers or compressors be de-emphasized in favor of the sealed cabin approach, since pressurization is dependent upon the presence of an atmosphere, thereby limiting the flight of man in a pressurized cabin to that very narrow range of altitude in which a compressible and non-toxic atmosphere can be found. There will always, of course, be a need for low flying, low velocity aircraft. For these the pressurization type of cabin with auxiliary oxygen will be the simplest and most economical to build and operate.

A self-sustaining "balanced aquarium" in space should be the ultimate aim of those concerned with this problem. A possible solution lies in a chemical, mechanical, or photosynthetic gas exchanger or combination of these for the maintenance of our gaseous environment.

Space flight is a fact; space travel is not. Whether or not space travel becomes a fact in our time depends upon the care with which we construct and maintain Man's Milieu in Space.

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THE ECOSPHERE OF THE SUN

by

Hubertus Strughold

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SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

The Ecosphere of the Sun

By H. Strughold, M.D., Ph.D.

THE source of all energy for the development and existence of life is ultimately the sun. Its rays create the physical and chemical environmental conditions found on earth; moreover, they participate creatively in the building up of organic substances. This biological efficiency of solar radiation, however, must naturally have its topographical limitations within the planetary system. Such a consideration ends ultimately with the problem of the possibility of life on other planets as a function of their distances from the sun.

The biological effectiveness of solar radiation, as far as its quantitative aspect is concerned, must be viewed from the standpoint of a general ecological principle, namely "the law of limiting factors" (F. F. Blakman, 1905), which is an extension of the "law of the minimum" (J. von Liebig, 1849) and of the concept of "cardinal points" (I. Sachs, 1860). In its simplest form, this law states that environmental conditions, such as temperature and light and the chemical components in air, water and soil, limit the activities of life if they are either too intensive and abundant or too weak and sparse. A certain minimum must be attained and a certain maximum must not be exceeded; only then can life exist. Between these two "cardinal points" lies a third one: the optimum of an environmental condition or of a combination of conditions. It is distinguished by the fact that here life processes attain their highest level. Beyond the extreme points, life may be possible in a latent state, at least for a certain time.

If we now apply these ecological rules to the life-supporting function of the sun, we arrive at a limited area or belt in the planetary system within which life of the kind we know (based on the carbon atom) is conceivable, where it is inconceivable outside of this zone. This zone is called the "ecosphere of the sun" in a recent publication by the writer.[10]

The syllable "eco" is derived from the Greek word "oikos," a house or environment. Hence, the ecosphere is an environmental sphere which can serve as the home of living organisms. The term "biosphere" is well known. It is understood as the organic world as a whole. Furthermore, biosphere is also understood to be the space in air, water, and soil which it occupies. Ecosphere is more comprising according to its literal meaning; it indicates not only *de facto* populated, but additionally potential living spaces.

Where in the solar radiation field of the vast planetary space is this area situated? As point of departure, we choose the radiation conditions as they are found in the distance of the earth from the sun (93 million miles). The

From the U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas. Dr. Strughold is chief of the Department of Space Medicine.

radiant energy received in this distance by one square centimeter area per minute in the form of heat, light, and rays of other wave lengths, is equal to 1.94 gram cal. This value, valid for the top of the earth's atmosphere, is long known under the name "solar constant." It was recently measured at an altitude of forty miles during a rocket flight.

As is well known, radiation falling vertically upon the area unit varies inversely with the square of the distance of the radiating source. At the distance of the orbit of Mars (141.7 million miles) from the sun, the solar constant decreases to a little less than half. In the area of Jupiter's orbit (483.9 million miles) it is only 1/27 of the earth's value. Pluto, the outermost of the planets (3,670 million miles) receives per area unit only 1/1600 of the amount of energy that the earth receives. In the distance of Venus's orbit (67.3 million miles), however, the solar constant is more than one-half and on Mercury (36 million miles) more than six times greater than the value of the earth. Such are the radiation conditions within gigantic globular shells, which must be imagined in the distance of the planetary orbits, concentrically surrounding the sun.

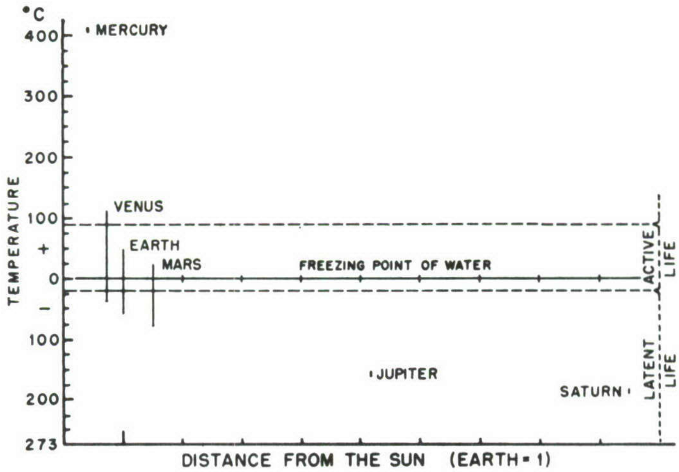

Fig. 1. Temperatures and solar distances of planets, and the temperature ranges for life.

The sun emits totally 10^{26} cal. per second, or, expressed in the dimension of the solar constant, 89,000 gram cal. cm.$^{-2}$ min.$^{-1}$. This is almost 46,000 times as much as the earth per square centimeter per minute receives at the border of its atmosphere.

TEMPERATURES ON PLANETS

If we now consider the measured temperatures of the planets, as they are found in recent astronomical literature, we obtain a set of figures which conform to a considerable degree with the values obtained from the respective solar constants (Fig. 1).

The temperature on the sun-side of Mercury amounts to over 400°C. That of the atmosphere of Venus varies between −10 and +100°C. On earth, temperatures between −60 and +60° C are observed. Martian temperatures range between −70 and +25°C. At the visible surface of the atmosphere of Jupiter, a temperature of −160°C is reported. For Saturn the figure is −180°C, for Uranus −190°C, for Neptune −220°C and for Pluto −240° C.[3,11]

Figure 1 further shows in what range of temperature active life, as we know it, is possible. In examining the possibility of life in any medium, *active* life is what counts.

If we include the thermophilic bacteria, the permissible maximum temperature rises to 80°C. The necessary minimum for active life is some 10 degrees below the freezing point of water.

This comparison shows that only Venus, the earth, and Mars cover partially or totally the range of biological temperatures required. Therefore, only these planets lie in the ecosphere, or more precisely in the thermal ecosphere of the sun. Venus lies in the warm, Mars lies in the cold, border zone, and the earth in the moderate middle of this *biotemperature belt.*

The conditions for planetary bodies within the intramercurial space might be compared best with those produced with a magnifying glass under the sun, and those in the trans-asteroidic space with deep-freeze conditions.

WATER ON PLANETS

Most important is the presence of water on planets in a biologically usable form, that is, in a liquid state. "Without water, no life." This would exclude the outer planets as biophilic celestial bodies because their atmospheres contain water only in the form of ice. Probably Venus must be omitted, too, because, up to now, no water has been detected in its atmosphere. Since the planet Mercury has no atmosphere, the presence of water is out of the question. Only the earth and Mars remain.

Shapley[8] recently termed that area in the planetary system within which liquid water is conceivable, the *"liquid water belt."* Without doubt this is an instructive and appealing term but it is related to one ecological factor only. The term "ecosphere" is a more general concept. It comprises the effects of the total electromagnetic spectrum of the sun.

OXYGEN ON PLANETS

One of these effects is the photodissociation of the water molecule by ultraviolet radiation. According to Harteck and Jensen,[1] and Poole,[7] water molecules at the border of the protoatmosphere of the earth (about 2½ billion years ago) have been split into hydrogen and oxygen in this way. The hydrogen escaped into space; the oxygen, because of its heavier weight, remained and started the transformation of the protoatmosphere, made up largely of hydrogen and hydrogen compounds, into an oxidized and free oxygen-containing atmosphere such as we have today. Significant reports on the chemistry of the earth's atmospheres and those of the other planets have been published by Kienle,[2]

Kuiper,[3] Slipher et al,[9] Urey[12] and Wild.[14]

Similar processes took place in the atmosphere of proto-Venus and proto-earth's atmosphere consisted of more than two billion years ago. Thus, the concept of the ecosphere of the sun is significant for the evolution of a

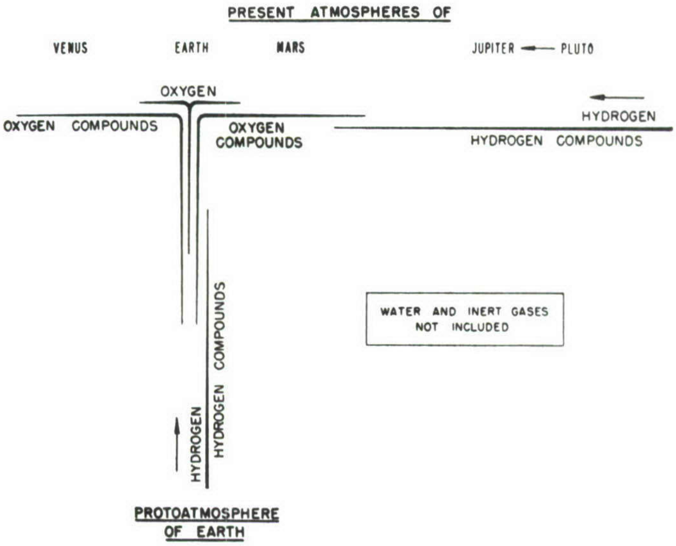

Fig. 2. The oxygen belt in the planetary system. The vertical line shows the chemical transformation from the protoatmosphere of earth to its present-day stage. The horizontal line demonstrates the transition from the hydrogen and hydrogen compounds containing atmospheres of the outer planets to oxygen and/or oxygen compounds containing atmospheres of the inner planets.

Mars. There, however, oxygen as well as hydrogen escaped into space; on Venus because of the high temperature in closer proximity to the sun, and on Mars because of its low gravitational force.

In this way, from reduced atmospheric conditions, oxidized conditions were produced. Only these conditions permit higher forms of life as we know it on earth. At a certain distance (beyond Mars) the radiation of the sun upon the planetary atmospheres diminishes to a point where it cannot produce this effect. Beginning with Jupiter we observe atmospheres consisting of hydrogen and hydrogen compounds—the same kind that the planetary atmosphere. The more distant planets are outside the possibilities of ecological development in so far as they depend upon the sun. In fact the planets from Pluto to Jupiter have retained their protoatmospheres up to the present day; they still show their original chemical constituents: hydrogen and hydrogen compounds. From Mars on to Venus the atmospheres of the planets are oxidized atmospheres. The earth, however, stands out with an additional high stock of free oxygen; it was able to accumulate free oxygen and to hold it. In the same way that we speak of a "liquid water belt" we may also speak of an "oxygen belt" in the planetary system. Appar-

ently, the transformation into atmospheres containing oxygen and oxygen compounds was possible only in a certain range of space around the sun (Fig. 2).

COMETS

The most spectacular example of the thermal and photochemical effect of solar radiation is shown by those celestial bodies which change drastically their distance from the sun: the comets. Coming from or from beyond the regions of the outer planets, these lumps of meteoric material, held together by various "ices" such as methane, ammonia and water develop, under the influence of solar radiation, gigantic atmospheric tails as soon as they approach closer than three astronomical units to the sun. These tails include OH, NH, CN, CO, et cetera, which are considered photochemical products of the aforementioned parent molecules.[11,13]

OTHER RADIATION EFFECTS

As we mentioned above, solar rays participate in the creation of organic material. The well-known example is the building up of carbohydrates in green plants by photosynthesis. This process is possible only between a certain minimum and maximum of the visible light irradiated. Too intensive illumination of a plant blocks photosynthesis, a phenomenon known to botanists as "solarization." Temperatures that are too high (45°C.) and too low (−20°C.) also bring photosynthesis to a halt. Therefore, this process is also possible only within a certain range at distances from the sun.

The same may be true of a process first suggested by Oparin,[6] in which organic substances such as amino acids might have been produced by ultraviolet radiation from hydrogen compounds in the earth's protoatmosphere. In this way the oceans may have been transformed first into solutions of organic compounds. On this "nutritional soup" (heterotrophic) organisms could have lived. Miller[5] recently reported he was able to produce amino acids in a chamber filled with a gaseous mixture of protoatmospheric composition by means of ultraviolet irradiation.

The ecological qualities of the planets naturally depend upon some other factors besides the distance of the sun. The planet's mass is one; its period of rotation, its heat production by radioactivity, the presence of an atmosphere, and the stage of evolution are the others. All this has been discussed by P. Lowell[4] in his classical book "The Evolution of the Worlds" in 1909. But the distance of the planets from the sun may be the predominating factor. Using a biological concept like that of the solar ecosphere makes this situation more understandable.

OTHER SUNS

A brief remark on the question of other suns with planetary systems may be in order. Harlow Shapley[8] estimated recently that out of more than 10^{20} stars in the entire universe, 100 million might have acquired planetary families. This being so, we might suppose that just as many stellar ecospheres are found in the universe. Shapley assumes further that, of the 100 million planetary families, perhaps one in 1,000 may have developed life in some persistence and on a higher level.

This estimate would yield one bio-

planet per one billion stars, or something like 100,000 in all. Assuming that a stellar ecosphere may offer room for more than one bioplanet, the number of planets in the universe that permit life may be even somewhat greater. Yet, all of this is, and probably must forever remain, a matter of delightful speculation.

SUMMARY

The ecosphere of the sun, or the helioecosphere, is a biologically defined concept. It indicates a zone surrounding the sun in which the radiation on the one hand does not exceed the ecological maximum, and on the other hand does not fall below the ecological minimum.

Considering the various ecological factors, we may speak of a "biotemperature belt," a "liquid water belt"[8] and an "oxygen belt" in the planetary system. They all lie in about the same area around the sun. Thus, the designation "ecosphere of the sun" may be an appropriate and general concept to cover all of them. The decisive factor is the distance from the sun. In our planetary system the ecosphere evidently extends from the area of Venus to beyond Mars, roughly from about 50 to 150 million miles distance away from the sun. The zone itself is therefore about 100 million miles wide. This corresponds to a mere 3 per cent of the total reach from the sun to Pluto, the outermost of the known planets. The solar ecosphere is therefore a relatively narrow zone within the planetary area.

The ecosphere of the sun represents a globular shell, in which planets in many different planes are conceivable, all enjoying the beneficience of the sun's radiance. But in our solar system all the planets revolve generally in about the same plane; therefore the area covered by the planets represents only a small section of that globular shell.

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THE UNITED STATES AIR FORCE EXPERIMENTAL SEALED CABIN

by

Hubertus Strughold

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

The U. S. Air Force Experimental Sealed Cabin

By H. Strughold, M.D., Ph.D.

MODERN rocket powered planes in which the breathing air is furnished from the ambient air, are attaining altitudes where the conventional pressurized cabins are becoming unsuitable for use.[5,11,20] This altitude limit is reached at about 80,000 feet for the following reasons:

1. *Technical.*—Because of the low air density, compressing the ambient air is technically prohibitive, due to the necessary weight and space requirements of the compressors.

2. *Thermodynamical.*—Compressing the rarified ambient air to a physiological useful range according to Mayo[11] would produce a temperature of about 400° F. in the cabin, which would be intolerable for the occupants.

3. *Toxicological.*—At about 60,000 feet a region of the atmosphere is reached in which various photochemical reactions occur, the most important of which is the formation of ozone.[17] By compressing the air of this ozonosphere or "chemosphere,"[8] the concentration of ozone may reach the threshold of toxicity.

For flights in the higher regions of the stratosphere, the conventional pressurized cabin must be replaced by a new type of cabin—the sealed cabin.

From the U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas. Dr. Strughold is chief of the department of Space Medicine.

Presented on March 21, 1955, at the annual luncheon meeting of the Space Medicine Association of the Aero Medical Association, Washington, D. C.

This type of cabin represents a hermetically closed ecological system in which the breathing air is not pumped in from the air outside the craft, but must be taken along at the start. The oxygen consumed by the occupants of the sealed cabin must be replaced from stores within the ship. The carbon dioxide must be removed, and temperature, humidity and odors must be controlled. These are the main problems involved in sealed or hermetic cabin flights.[2-4,6,12,13]

While the altitude limit for the use of oxygen equipment lies at about 40,000 feet, and for the pressure cabin at about 80,000 feet, the sealed cabin has no limitation on altitude. This type of cabin gives us the green light into space.

The forerunner of the sealed cabin was the sealed gondola used by the Piccard brothers[14] and by Stevens and Anderson in their record breaking balloon flight of 72,395 feet in the *Explorer II* in 1934.[18] The areomedical knowledge gained from the latter flight has been evaluated by Armstrong, in a paper published in 1936.[1] A more general review of the problems involved in sealed compartments has been reported by Fenno.[6] The knowledge gained in submarines and bathyspheres is also of great value.[15] However, the coming development of the hermetic cabin craft will make necessary more detailed and specific studies.[9,10,16] The possibility of carrying out such studies on the ground are offered by an exper-

imental sealed cabin. The construction of such a chamber was initiated in 1952 by this school from blueprints designed by Dr. Fritz Haber. The chamber was constructed by the Guardite Company of Chicago, Illinois, and delivered the summer of 1954. (Fig. 1.)

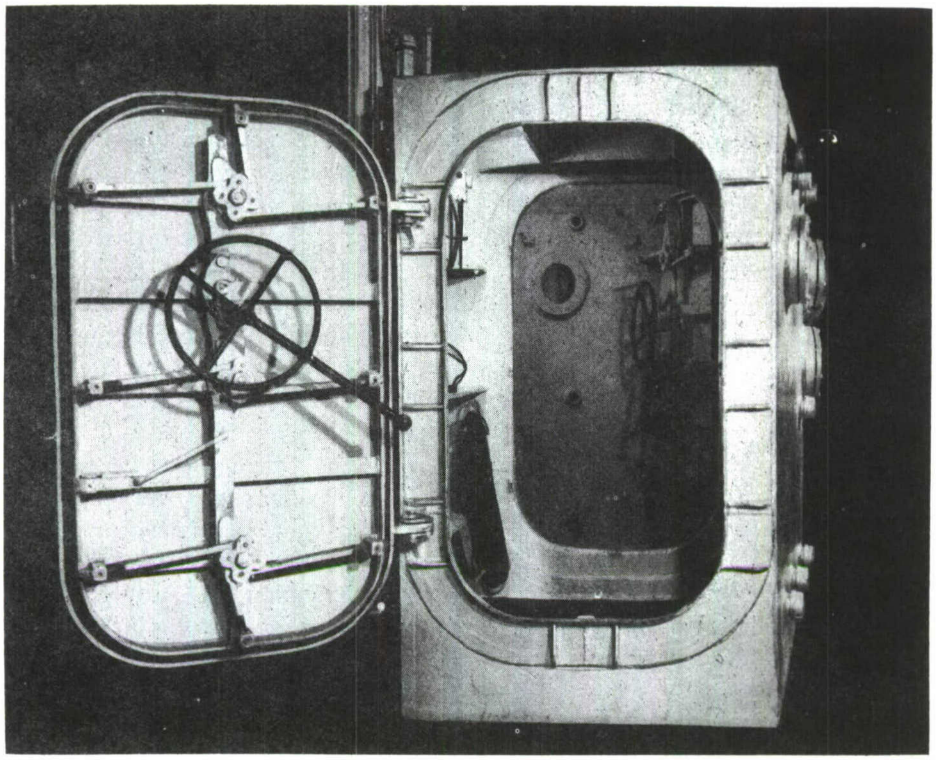

Fig. 1. The experimental sealed chamber of the U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas.

The experimentation program for this experimental sealed cabin is a combined research project of the space medicine and of physiology-biophysics. It is not within the scope of this paper to discuss the various research tasks. I would like to say, however, that the project involves two main problems which warrant investigation:

1. To what extent, and in what direction, are the various climatic factors changed by the presence of occupants in the cabin.

2. How can these changes be counteracted by physical, technical, or biological means.

This experimental chamber also can serve as a training device to indoctrinate the occupant with the problems encountered in a closed ecological system and to familiarize him with the procedures necessary to handle any emergency situations such as the failure of the automatic control systems and an eventual puncture of the cabin itself.

The Air Force experimental sealed cabin is a prototype of the cabin that may be built into future space ships. This type of cabin will also be required in the coming phase of "global space-equivalent flight" at supersonic speed through the space-equivalent regions of the atmosphere.

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PERSONAL EXPERIENCES DURING SHORT PERIODS OF WEIGHTLESSNESS REPORTED BY 16 SUBJECTS

by

Siegfried S. Gerathewohl

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Personal Experiences during Short Periods of Weightlessness Reported by Sixteen Subjects[1]

By

S. J. Gerathewohl[2]

(*Received June 18, 1956*)

Abstract. A series of experiments on weightlessness was conducted using a Lockheed T-33 type aircraft for dives and parabola flights yielding practical weightlessness from 10 to 30 seconds duration. Records of the personal experiences of sixteen subjects during these states were obtained by interviews, pilot reports, and written statements.

Results: The majority of our subjects felt very comfortable during weightlessness; several subjects reported sensations of motion with no emotional involvement. A small group of subjects experienced discomfort, nausea, and severe symptoms of motion sickness.

Tolerance to weightlessness is discussed with regard to space flight. It is theorized that individuals differ significantly as to their susceptibility to sub- and zero-gravity and their adaptability to weightlessness. If the right persons can be selected and adapted, some earlier concepts about artificial acceleration or "quasi-gravity" of space vehicles can be revised.

Zusammenfassung. Ein Strahlflugzeug vom Typ Lockheed T-33 wurde für Versuche im andrucklosen Zustand verwendet, wobei im Sturz- und Parabelflug Andrucklosigkeit für die Dauer von 10 bis 30 Sekunden erzielt wurde. Einsicht in die Erlebnisse der Schwerefreiheit ergab sich durch Aussprachen und Interviews, Angaben des Piloten und schriftliche Berichte der Versuchspersonen.

Ergebnisse: Die Mehrzahl der Versuchspersonen erlebte den Zustand der Schwerefreiheit als angenehm; mehrere Personen berichten gefühlsneutrale Bewegungssensationen wie Fallen, Schweben und Drehempfindungen. Eine kleine Gruppe empfand den Zustand als unlustbetont und zeigte Symptome, die für die See- und Luftkrankheit charakteristisch sind.

Die Frage der Toleranz gegenüber der Schwerelosigkeit wird in Hinblick auf den Raumflug diskutiert. Es scheinen erhebliche Unterschiede zwischen den Individuen zu bestehen, sowohl was Toleranz als auch Anpassungsfähigkeit betrifft. Wenn man die geeigneten Personen auslesen kann, wird man auf die Einführung einer Dauerbeschleunigung oder „Quasi-Gravitation" bei Raumschiffen verzichten können.

Résumé. Une série d'expériences a été conduite à bord d'un avion Lockheed T-33 suivant une trajectoire parabolique ou de piqué en vue de neutraliser le champ de la pesanteur pendant une durée de 10 à 30 secondes. Les sensations éprouvées par seize sujets ont été recueillies soit par les rapports des pilotes ou par interviews et déclarations écrites.

[1] This paper was presented at the Seventh International Astronautical Congress in Rome, September 1956. — Opinions expressed herein are solely those of the author and in no way reflect the official views of the Department of Defense or the United States Air Force.

[2] School of Aviation Medicine, U.S.A.F., USA.

Résultats: La majorité des expérimentateurs ont trouvé la période de suppression de la pesanteur agréable; quelques uns ont éprouvé des sensations de mouvements sans réactions émotives. Un petit nombre s'est trouvé sujet aux symptomes caractéristiques du mal de mer et de vol: nausées et sensation d'inconfort.

La tolérance vis à vis de la suppression de la pesanteur est envisagée en relation avec le vol interplanétaire. Il semble que la réduction et la suppression de la pesanteur peut affecter les sujets de façons sensiblement différentes et que les capacités d'adaptation sont aussi variables. Si une sélection peut être faite en vue de l'adaptation certaines idées antérieures sur la nécessité d'une pesanteur artificielle dans les astronefs doivent être révisées.

In space flight operations, sub- and zero-gravity states will occur for considerable periods of time [1—8]. The psychophysiological condition associated with these states is designated as weightlessness and has been treated as a subject of scientific concern in numerous papers during the past seven years [9—17]. By and large, these treatises deal mainly with the phenomenon of weightlessness in a rather theoretical way, or they contain experimental data on alteration of performance during the weightless state. Only sporadically one finds reports about personal experience of weightlessness; and the few reports available from individuals having firsthand experience are almost shamefully hidden in an inconspicuous paragraph at the end of some research papers [13, 20, 23]. However, in the experience of every pilot or person, who was exposed to the weightless condition for at least a few seconds, there are certain symptoms that he interprets as weightlessness, and that manifest themselves as sensations being predominantly subjective in nature on the one hand, and as changes of performance on the other, the latter being chiefly distinguished by an overt and pronounced tendency of objectivation.

Before we attempt to demonstrate some of the problems involved in human behavior during the weightless state, we must discuss the problem of personal experience somewhat further. There can be no doubt that the differentiation between "sensations" on the one side, and "performance" on the other side, is an artificial one because both factors are so closely linked together and interrelated that any separation can serve as a working hypothesis only. It is mainly for the sake of a schematic classification of symptoms that we confine ourselves to the treatment of the "subjective" or personal experiences of weightlessness. Actually, changes in gravity, acceleration, and weight stimulate our mechanoreceptor organs which in turn discharge impulses to the brain. We have enough reason to assume that particular discharge patterns brought forth by changes of the weight of the otoliths induce harmless or even pleasant sensations as well as serious somatic disturbances associated with these changes. Thus, psychological and somatic effects of weightlessness may stem from the same labyrinthine source; and they may affect the well-being of the individual as well as his task performance.

The symptoms of weightlessness are manifested in many ways, and they are experienced so differently by man that thus far no clear picture about their effect has been obtained. Weightlessness nevertheless becomes an important environmental condition in the flight operation of tomorrow; and we must scratch together every bit of information available today. Unfortunately, it is true that it can be produced only in circumstances not very favorable for experimentation; and that zero-gravity can be achieved for only about 30 to 40 seconds at present. However, its importance cannot be ignored merely because of these limitations; and we believe that one can extrapolate more successfully and make valid predictions, the greater the amount of research data, and the

closer we inspect the variety of personal experiences obtained during the weightless state. An attempt is made in this report to present the existing data concerning subjective experiences during weightlessness, and to clarify some of the problems concerning human tolerance to exposure to short periods of reduced gravity.

Method

During the years 1955 and 1956, a series of experiments on weightlessness was conducted at the USAF School of Aviation Medicine. The study, performed by the Department of Ophthalmology in conjunction with the Department of Space Medicine, concerned eye-hand coordination under conditions of increased and decreased acceleration. In general, it was thought to study human behavior and to delineate the aeromedical implications of weightlessness.

Weightlessness, or at least a state of minimum gravity, was produced by flying the aircraft in a Keplerian trajectory or in a 40 degree dive. The aircraft used was a Lockheed T-33 A powered by a J-33 A-35 engine developing 4,600 pounds of thrust. The operational altitude for both flying maneuvers was between 20,000 and 17,500 feet. The pilot of the craft, Major HERBERT D. STALLINGS, USAF, flew the ascending arc of the parabola at full throttle, the descending part with about 75 percent r.p.m. in order to obtain weightlessness for about 25 to 30 seconds. During the dive, sub- and zero-gravity states of about 15 seconds were obtained. The study of eye-hand coordination consisted of a simple aiming test in the weightless state; and an additional experiment on stress was conducted by the Department of Pathology, School of Aviation Medicine, using some of the subjects and the same flight pattern in conjunction with our tests. Finally, a special experimental design was developed for assessing human tolerance during brief periods of weightlessness (see Appendix).

At the end of each sub- or zero-gravity flight the subject was asked to write a brief account of his experiences of weightlessness. He was told to describe rather casually his sensations including such phenomena as fall tendency or response, anxiety, and other emotional and autonomic reactions during reduced weight. Furthermore, the pilot and the flight surgeon who saw the subject during and after the flight, recorded symptoms of behavioral changes at the flight line. These data and the statements of the subject were collected at the end of the experiment and used for this study. Unfortunately, not all of the subjects complied with our request to furnish personal reports; and this is particularly true for those who evidently had shown adverse symptoms of weightlessness. Since not only interest and motivation but also age and flying experience may have some bearing upon the experience of reduced gravity, an abstract of the flight record of the individuals who participated in this study is given prior to the personal data. In all cases of subjective reporting, the story is given in the subject's own words. In the other cases, the observations are described as they were recorded by secondary sources and related to the particular individual. After all the data had been collected, they were classified with regard to the mode of personal experience.

Results

I. Sensations of Comfort and Pleasantness

1. Subject *H.D.S.*, pilot; age: 35; about 1,000 jet hours.

"During the experiment which involved numerous flights, over 200 parabolas and several different subjects, I had an opportunity to observe my personal reactions

as well as those of others. In the beginning of each parabola, the release of the positive pressure of the body against the air-frame tends to bring about a momentary dissociation between the pilot and the aircraft. As the zero-gravity state is continued, however, this mental condition seems to disappear. A slight change of pressure is noted in the ear drums but in no way impairs the hearing sense. A lifting sensation that resembles pressure on the lower portion of the eyeballs is felt but failed to prevent the eyes from functioning normally.

"Movements of the extremities is effortless and no trouble with muscular coordination was experienced. Orientation of aircraft in relation to the ground was unaffected. "Up" was still up, and "down" appeared to be still in the right direction.

"For my personal conclusion, the state of weightlessness is a pleasant feeling. There were no adverse effects to my sight, hearing, breathing, or muscular coordination during this condition. At first, there were slight errors in judgment as I reached out to change the power setting and to turn off the different fuel switches, but I found that automatic compensation took place during later parabolas. It would appear that from experience gained during this project, prolonged states of weightlessness would not impair the physical performance, physical condition, or mental well-being of the future pilots of space."

2. Subject *E.S.G.*, Captain, USAF (MC); age: 26; flying and jet experience.

"On 21 September 1955 I participated in a T-33 flight, during which time 9 parabolas were flown. Six were done while I was under the hood; the last three with the hood pushed back. My subjective reaction was essentially similar in both situations. During the actual period of weightlessness there was no unpleasant sensations. If anything, it was a mildly agreeable situation. My eye-hand coordination was only slightly impaired, if at all. If I had the opportunity of more practice under the weightless condition, I feel that my eye-hand coordination would rapidly become as good as under normal gravity. During the period of increased positive "*g*'s", I would start aiming for a point somewhat above the center, in order to hit the center of the target. If the "*g*'s" would decrease during this maneuver, my final mark would be somewhat above the central point. There was no similar necessity to aim for a point beneath the center of the target while undergoing the weightless condition."

3. Subject *R.S.F.*, Colonel, USAF (MC); age: 45; long flying and jet experience.

"By constantly balancing the stilet in my hand and tossing it in the air I was able to detect rather accurately when entering the weightless state. In addition, a slight loosening of the seat belt caused me to rise from the seat and be held against the belt so that there was a total absence of "seat of the pants" sensation while in the weightless state. The mental sensation of weightlessness can best be described as one of incredulousness or even slight amusement. The incongruity of seeing objects and one's own feet float free of the floor without any muscle effort can only be described in those terms. It seemed that lifting my arms or performing movements with my hands had to be evaluated in the terms of resistance against overshooting."

4. Subject *R.M.R.*, 1st Lt, USAF; age: 31; completed training as paratrooper in 1944; flying experience; no previous jet experience.

"An initial reaction of acute anxiety and confusion lasting about five seconds followed by a marked feeling of well-being for the duration of the first parabola (six parabolas were executed). Upon entering the second parabola, a mild anxiety reaction lasting one or two seconds, followed by a feeling of well-being for the duration of the maneuver. Pleasant anticipation immediately preceding the remaining parabolas followed by the feeling of well-being. Little or no anxiety.

"The "feeling of well-being" is somewhat analogous to the relief experienced upon removing a heavy burden, such as a back pack, carried for a prolonged period. However, closer introspection seems to indicate that the sudden experience of "floating in space" temporarily allays or overcomes fear of falling; i.e., "I am weightless, hence I cannot fall". I have noted a similar paradoxical feeling of well-being during the experience of "weightless" free-falling in the course of parachute jumping.

"No visceral sensations were noted during zero-gravity. No subjective differences were noted between sensation of zero-gravity under the hood and with visual contact.

Within the scope of the test described above, psychomotor adaptation to zero-gravity was extremely rapid. Normal gravity performance was obtained or excelled within 15 seconds of weightlessness."

5. Subject *J.B.B.*, A/2 C; age: 23; about 300 hours as passenger in conventional type aircraft; no previous jet experience.

"When we were over the testing area, Maj. STALLINGS told me to pull down the hood and prepare for the test. This I did. I held the stylus against the mask, and centered my eyes on the center of the target. My only thought at this time was to hear the signal to begin correctly. I first felt an increase in gravity, and then we went into zero-*g* condition. Maj. STALLINGS gave me the signal: zero-gravity, and I counted three, then I struck the target with a quick thrust. I was surprised at my close hit, because I had expected it would be difficult to hit. I had not previously spent any time in thinking where the hit was expected to be, but after the first seconds of zero-*g* I expected the hit would be high. I did not consciously try to compensate this expectation.

"During zero-*g* condition, I felt as if I were floating in the air, restraint only by the seat belt and shoulder harness. It seemed a rather pleasant sensation. I was not surprised or particularly impressed by the zero-*g* condition. When we recovered normal gravity, Major STALLINGS told me to change targets and he would tell me when I should strike the second target. The next five targets went by mechanically. I followed the same procedure as with the first target. I do not recall thinking about anything but concentrating intently on hearing correctly the instructions. When the six targets were finished, we did a roll to the right and then to left. I then raised the hood and Maj. STALLINGS demonstrated the zero-*g* procedure. I raised my hand under positive *g*'s and under zero-*g*. I had difficulty raising my hand when under positive *g*'s; and my hand seemed to float under zero-*g*."

6. Subject *W.J.Y.*, A/2 C; age: 22; about 300 flying hours; previous jet experience in 5 rides with B-57.

"Major STALLINGS gave me a final briefing on the test as we climbed to 20,000 feet. After we reached altitude, I pulled the hood over my section of the cockpit. We cleared the area and dropped off into a dive to gain airspeed. Major STALLINGS counted off the seconds before pullout so that again, as through the entire flight, I was forewarned of the maneuver.

"The pullout was about 3 *g*'s for a five second duration; then over the top and into the weightless condition. I made my strike and informed the Major. We then prepared for the succeedings runs and accomplished them in like manner. At the end of the last run we climbed to 20,000 feet and did our two rapid aileron rolls. One to the left and one to the right. The rolls didn't seem to have any effect on my sense of balance nor did I feel sick at any time. I kept track of the position of the aircraft by means of the artificial horizon.

"At the completion of the rolls I pulled the cockpit hood off and Major STALLINGS put the aircraft into a sustained parabolic path to give me a chance to mentally record my feelings and reactions while in a weightless condition.

"The weightless condition brought on an extreme feeling of well-being and comfort. At no time did I have the sensation of falling. The sensation of lack of physical support was also strangely missing. It was what I would suppose animated suspension might feel like. All my internal organs were comfortable, and I maintained normal mental activity. As the period of weightlessness lengthened I could feel my body relaxing. Actually, I've never been so bloody comfortable in all my life; and I think that if I had my choice of places to relax, a weightless condition would be definitely it. I must add though, that at no time did it have a drugging effect on me. I feel perfectly confident that I could carry out any assigned duty for the usual length of time without any interference other than teaching myself to coordinate my muscles under a weightless condition."

7. Subject *N.G.M.*, 1st Lt, USAF; age: 28; 1600 hours as fighter pilot; gunnery instructor since 1953 on T-33, F-80 A, B, C, F-84 G, and F-86 E and F.

The subject took a pad along during the flight and made short notes after the dives and parabolas. The flight pattern consisted of 4 dives, the first three with hood closed, and one series of four parabolas producing practical weightlessness up to about 30 seconds. The subject unfastened the safety belt during the parabolas and let himself float in the cockpit. He had no sensations of motion during the weightless state.

Here are his notes:

1. Dive: felt light (enjoyed it).
2. Dive: same feeling.
3. Dive: same feeling, no sensations (of motion, that is. The author).
4. Dive: no difference.
5. No difference (no belt).
6. No difference, enjoyed.
7. No difference, enjoyed.
8. No difference, enjoyed.

The subject supplemented his statements during the interview following his flight by telling about experiences of weightlessness during gunnery missions. He feels that jet pilots may have the best tolerance to sub- and zero-gravity.

8. Subject *L.A.K.*; Major, USAF (MC); age: 40; about 250 hours conventional type flying, including 6 weeks' flying training; 14 jet hours in T-33.

"During pushover (with hood closed and eyes open) slight but definite sensation of viscera being displaced upwards. No nausea, no disorientation with respect to cockpit environment. During weightless dive pleasant sensation of complete relief of muscular stresses. Part of this sensation might have been due to release of weights of clothing, chute, and helmet. No loss of motor coordination on attempted reaching for controls and instruments. Reaction effect of pushing against floor, raising arms, etc. not tested, as seat belt kept fastened. Pullout not remarkable.

"*Hood closed, eyes closed:* Physical sensations identical with dive 1. No sensation of disorientation or falling. Sensation of floating on air. No concept of orientation with respect to any external reference. No dizziness or nausea. Pleasant sensation of release of all muscular stress.

"*Dive 3: Hood open, eyes open.* Sensations same as for dives 1 and 2. No discomfort, no disorientation. Visual reference with ground provided no sense of illusion. No dizziness or nausea. No sense of falling or loss of support except as visual orientation demonstrated position and direction of movement with respect to plane of earth surface. Arms and legs were raised, and weightless state demonstrated with small free floating object in cockpit. I would describe the entire sensation as very pleasant.

"*Series of 4 consecutive ellipses:* During this phase of the flight, concentration was made on attempting to evaluate the effect of oscillating head motion (side to side) during zero-*g* ellipses and approximately 3-*g* pull-outs. During zero-*g* no untoward effects whatever were noted. During positive-*g* there developed, by about the last pull-out, slight sensations of nausea.

"During the ellipse the sensation was again one of pleasant lightness and stimulating release from some ubiquitous load. I had the feeling that once compensated by short training to operate in the zero-*g* medium coordinated movements might be much more rapid and accurate than under normal conditions. The alternation of zero- and positive-*g* produced no particular disorientation or vertigo inasmuch as ground reference was not lost.

"The letdown was performed rapidly, on the order of 5000 to 6000 fpm accompanied by much turning and banking. It was noted that even slight head movements under the conditions of continuous but changing degree of linear (dive brakes) and radial acceleration rapidly produced symptoms of motion sickness manifested by dizziness, sweating, and severe nausea, necessitating switch to 100% oxygen."

II. Sensations of Motion

1. Subject *J.R.W.*; A/2 C; age 22; 250 flying hours during pilot training; 80 hours T-33.

"I felt no adverse effects during or after the zero-gravity period physically or otherwise. There was no symptom or change from the normal feeling that I noticed. As for subjective sensation and personal opinion, I like this state as a change from the ordinary, the floating feeling, at the weightless condition: it seems odd but not distasteful to be relieved of the task of holding up your own body and move without any effort."

2. Subject *J.M.Q.*, Major, USAF (MC); age: 42; about 400 flying hours; no previous jet experience.

"This afternoon I rode with Major Stallings in the SAM T-33 and experienced approximately 6 parabolic trajectory flights producing the short "zero-*g*" state.

"The most remarkable sensation was one of having begun a "back-flip" and becoming suspended with the back horizontal, face upward. I have done a fair amount of tumbling on gymnastic teams in high school and college. The sensation in the flight was one of having started a "back-flip" from a standing position and then becoming "hung-up" part way over — looking toward the sky but not completing the flip. It was important to note that there was no continuous feeling of motion once this feeling of a partial backward tumble reached the inverted position.

"There was no particular enjoyment nor dislike for the maneuver. Instead a feeling of indifference. No somatic sensations referable to viscera — such as sinking stomach, etc. Perhaps a longer flight with more runs would be indicated since there was no sensation of motion sickness from the few runs experienced.

"The flight was taken without a hood enclosing the cockpit so that visual references outside were available. However, I found myself ignoring the outside environment — not bothering to look for my orientation with reference to the ground."

3. Subject *S.J.G.*; age: 46; flying experience as glider pilot and passenger in conventional type aircraft; 1 jet hour.

"The one-hour familiarization flight in the T-33 included 3 parabolas with sub-gravity states lasting about 15 to 20 seconds each. The maneuver started with an increase in acceleration of about 3 *g*'s, then a short subgravity state of about 5 seconds during ascend and about 10 seconds during the dive after the pushover. During recovery, about 2—3 *g*'s were indicated.

"I had my eyes open during the first sub-gravity state. Nothing peculiar happened short of the feeling of hanging loose in the shoulder harness during the initial fall sensation which felt like that experienced during a sudden down-draft. I looked at the *g*-meter and saw the pointer on zero. There was also a short feeling of being slightly rotated around the lateral axis of the body like during a swan dive. This occurred during the push-over and may be due to the pitching movement of the airplane. No feel of up and down during the weightless condition; but pronounced weight sensation directed toward seat and feet during pull-out.

"I closed my eyes during the second sub-gravity maneuver. There was no apparent movement of the reddish lid background; but the eyes were closed after the zero-state had been reached. The orientation was completely lost during this phase but shoulder harness and safety belt furnished intermittently tactile clues as to suspension. The personal sensation associated with it was not unpleasant nor scaring; but uncomfortable feeling during the pull-out. This caused a slight attack of nausea; and I switched to 100% oxygen and had temperature lowered.

"I let the safety pin float during the third parabola, but it floated for 3—4 seconds only during the last part of the dive. During all three parabolas, the movement of the aircraft and slight accelerations served as orientational clues. The feeling of unpleasantness increased and I had slight attacks of motion sickness during the flight, was fatigued afterwards, and had headaches until about 3:00 p.m.

"The second flight of about 1 hour included four push-overs and sub-gravity for 15—20 seconds each. During the entry into the parabola, I felt a slight lift sensation with dangling in the harness and safety belt. There was a definite sensation of falling during the transition from increased to decreased gravity enhanced through the diving experience in the plane. Subjective sensation was not too pleasant.

"The third flight involving the aiming test was very comfortable, and I felt no unusual strain during and after the flight.

"No difficulties were observed during the sub-gravity state in flight test No. 4. The experiment was closed with two slow rolls in either direction. This caused an illusion of apparent motion just like in the BARANY chair. Furthermore, a slight dizziness and motion sickness spell was felt, so that I switched to 100% oxygen during the return home; but this may have been due to the increased acceleration during pull-out and the rolls, because I felt all right during the sub- and zero-gravity states.

"There was no sensation of being hindered during jabbing at subgravity. Moving the arm is very light since the arm tends to float during aiming and hitting. I had a scotoma for about 20 minutes 1 hour after landing."

The experiences in the additional flights can be summarized in that the weightless condition was neither a very pleasant sensation nor was it associated with severe symptoms of motion sickness. In some of the experiments the subject felt quite well, in others a slight dizziness, sweating, headaches, and fatigue were noticed. Concentrated insight during weightlessness with eyes closed yielded a feeling of backward rotation which started with the sensation that the head gets bigger and flips backward, and then the body follows as if one were in an inverted position. However, no sensation of falling or of moving with increased velocity was observed during this state.

III. Sensations of Unpleasantness and Psychosomatic Symptoms

1. Subject *J.R.K.*, Captain, USAF (MC); age: 31; about 1000 hours flight in conventional type aircraft; two hours jet flying including acrobatics in T-33.

"Following take-off climbed to 20,000 ft. and leveled off. Flew straight-and-level for several minutes prior to parabola flight. No apprehension — no evidence of motion sickness. Had previously flown in excess of 1000 hrs. including 2 hrs. in T-33 performing acrobatics (1 week ago) with no evidence of motion sickness.

"With hood in place pilot begun 1st series of 6 parabolas with weightless or zero-gravity state produced for 10 to 15 seconds.

"Following 1st and 2nd parabolas had a feeling of discomfort — hunger sensations — uneasiness and slight fatigue. The feeling of nausea increased on fourth parabolic maneuver; switching to 100% oxygen brought no appreciable relief. Had sensation of increasing uneasiness and nausea. At the height of the parabolic arc it felt like my stomach was in my throat; I begun to look foreward to the plus *g* maneuver on pull-out at which time my stomach would feel like it were in proper position again. At the completion of the fifth zero-gravity state I knew it would only be a matter of time before an emesis would occur; I was aware of a slight regurgitation on the fifth. Fought the sixth maneuver desperately with continued swallowing, holding my mask in place, with burp bag in readiness. Had we continued the procedure one or two more times I would have been unable to retain the small breakfast I had consumed that AM.

"At the completion of the parabolas 2 rolls were performed with no increase in symptomatology. I noticed no unusual equilibrium disturbances during the flight.

"Following completion of flight felt uneasy and fatigued. Did not return to normal state until after a heavy noon meal."

The subject was flown in accord with our new flight pattern five months later. He reported the following experiences during the second experiment:

"Following take-off we developed a runway trim in full down position which was controlled after 5 minutes, and then climbed to 20,000 feet and leveled off. Unable to close instrument hood — wedged between seat and canopy — to simulate hood, I lowered visor and stared directly at cockpit instruments.

"First dive — normal sensations (eyes open). Second dive — sensation of floating out of seat and begin to turn in backward sommersault. Third — by looking outward

normal sensation of raising out of seat, falling weightless. Fourth — suspended arms and pencil in midair.

First parabola — looking at instruments: normal sensation of zero-gravity, floating out of seat, etc. Second parabola — moving head in vertical plane slowly — no unusual symptoms. Third parabola — moving head in horizontal plane — no vertigo. Fourth parabola — combining vertical and horizontal head movements — no disorientation.

"During last two parabolas switched to 100% oxygen; had slight "giddy" feelings in stomach but nothing to compare with previous flight. Two slow rolls to right and left — no untoward reactions. Had eaten a bowl of cereal and milk and slice of toast just prior to flight which may have helped to prevent nausea experienced on first flight."

2. Subject *C.P.D.*, Aviation Cadet, USAF; age: 20; active in flying training as pilot trainee; some jet experience in T-33.

The subject experienced the first troubles on the merry-go-round and on the Ferris wheel. He is highly motivated for flying. First symptoms of air sickness during primary flying. He vomited already in the Piper Cup. Later difficulties especially during stalls and acrobatics.

The subject flew parabolas with Major Stallings on August 10, 1955. He reported that he became motion sick through changes in acceleration. He observed no unpleasant feelings during sub- and zero-gravity, but the changes in stomach weight seemed to have produced symptoms of nausea. He let his arms float during the weightless state.

Major Stallings reported that the patient became sick during the weightless state; he observed him in the rearview mirror and cut the flight short because of the patient's complaints, which the latter described as 'getting hot', and feelings of nausea and the urge to vomit. The pilot flew two continuous slow rolls at the end after the patient had 100% oxygen and cold air.

3. Subject *A.G.B.*, T/Sgt, USAF; age: 35; 1500 pilot hours; several flights as passenger in jet type aircraft.

"At approximately 1100 hours, 11 October 1955, Major Stallings, Pilot, and I took off in T-33 for my first flight at zero-gravity. Upon reaching proper altitude I pulled the hood over rear cockpit, and awaited my instructions from Major Stallings. I had no visual reference with the horizon, nor anything outside of the cockpit. The first run at zero-gravity was uneventful, and I performed my task. During the second run, after I performed the task, I had a sensation of feeling that I was going over (float or fall) the instrument panel. I was not scared, but I wanted to place my hands on the instrument panel to catch myself, but I knew I was not going to move, and I kept my hands to my lap. After the third run I complained to Major Stallings that I was sweating and asked for lower temperature and better ventilation, and he adjusted same. I noticed a feeling of nausea. After the fourth run, and after performing task, the feeling of nausea increased. After performing the task on the fifth run I again had the sensation of going over the instrument panel, but again kept my hands in my lap. The nausea increased slightly, but the ventilation and decreased temperature had made me feel more comfortable. I switched to 100% oxygen temporarily, and tried to slow down or regulate my breathing in preparation for the sixth run. After the sixth run, my task was completed, the nauseated feeling increased again, and I explained this to Major Stallings, and he instructed me to go to 100% oxygen. I pushed the hood back, and Major Stallings performed one more run at zero-gravity, at which time I had visual reference with the horizon, and the nauseatic feeling was beginning to subside. At no time did I vomit nor have a feeling that I was at the verge of vomiting, although the nauseated feeling was there.

"I had an ill fit in my oxygen mask, and was quite uncomfortable while under the hood and subjected to 1.5 *g* and zero-gravity. For about two hours after the flight, and even though I had eaten lunch, my stomach had a mild upset feeling. Upon arising the morning of 12 October 55 my ears were plugged, with a very mild

occasional pain. This I believe to be due to 100% oxygen breathing, as it has previously been explained that this is a possible after-effect."

The subject repeated the zero-gravity experiment on November 2, 1955, but did not turn in a report about his personal experience during this flight. He felt "normal" according to his own statement and that of the pilot. Since the subject was under the effect of drugs (Benzedrin) at that time, the result is not conclusive.

4. Subject *F.G.H.*, A 2/c; age: 20. A few passenger hours, no previous jet experience.

The subject participated in an experimental zero-gravity flight on December 5, 1955 from 14^{55} to 15^{25} p.m. The flight consisted of dives rather than parabolas for obtaining zero-gravity yielding no noticeable increase of g during recovery. The subject developed extreme nausea after three zero-gravity states and vomited during the flight. He would not participate in further flights and did not turn in a report on his personal experiences during the weightless state. He was free of cold, allergy, etc., and had no medication in the last 24 hours before the flight.

5. Subject *F.N.R.*, Captain, USAF (MC); age 27; appr. 150 passenger hours in conventional type aircraft; no previous jet experience.

"During the first episode of weightlessness in which the canopy canvas was pulled forward and closed, I had the particular sensation of levitation. It was very easy to breathe, I had no sensation of nausea and everything seemed delightful.

"During the second weightlessness test in which my eyes were closed, I had the sensation that I was in nowhere particular due to the fact that I had lost the visual stimulus of the cockpit. However, I felt the same way, very light, as if floating in the air but there were no untoward effects.

"During the third episode of weightlessness I floated a burp cup suspended in the air and it was very easy again and pleasant to feel sensation.

,,In the series of parabolas I had some sensation of nausea it seemed following each sensation of positive g. I felt no sensation of nausea during the positive g, but when I left the duration of positive g and entered the field of zero-g, I felt somewhat nauseated. However, there was no salivation although there was some slight generalized sweating. I was able to shake my head successfully very easy. No sensation of difficulty encountered in weightless period. Hard to shake head up and down under 3 g's; no trouble to and fro.

"During the two rolls, one to the left and one to the right, I experienced the sensation that I was looking into a large spherical mirror but this did not seem to have any ill effects. My eyes were focused on the horizon and the clouds and I did not close them during any of the rolls.

"After finishing the rolls we flew for approximately ten minutes over the city of San Antonio and surrounding area and then returned home. When we made the initial dive to descend I began to feel somewhat nauseated and although we left 20,000 feet, by the time we hit 12,000 feet I began to have emesis. We then returned home and landed uneventfully.

"Immediately on going home I felt very limp and weak, somewhat tired and sleepy. I rested for approximately an hour and a half to two hours and ate some food and then felt much better. Throughout the afternoon following the flight I felt somewhat fatigued generally with occasional wave of nausea. However, I was able to carry out my work satisfactorily."

Discussion and Conclusions

To date, the experiences of 16 human subjects have been studied in controlled experiments yielding more than 300 dives and parabolas. During the brief exposures of 10 to 30 seconds of practical weightlessness, various degrees of tolerance to this state were observed; and some of the individuals' experiences varied when the experiment was repeated. From the reports given in the preceding paragraphs it appears that exposure time and practice seem to be of great importance for the behavior in and the adaptation to the weightless state.

However, it has been voiced that one cannot generalize from these short exposures because they do not permit extrapolations as to either adjustment of the organism to weightlessness, or to the aggravating effects of the autonomic disturbances observed. SIMONS [18] (1955) is somewhat critical in this respect by stating that the motion sickness syndrome normally needs some time to develop; and he writes in this connection:

> "When the ocean suddenly becomes rough, it takes an appreciable time of exposure, something on the order of 15 to 20 minutes, before most neophyte passengers become thoroughly sick. Many hours later the seasoned sailors are still unaffected. There are many similarities between the factors producing motion sickness and its possible counterpart, space sickness. The differences are sufficient that there may or may not be the same 20-minute latent period upon initial exposure with acclimatization after repeated or prolonged exposure."

This situation is to some extent similar to that of about 50 years ago, when the WRIGHT brothers succeeded in maintaining their craft airborne for about the same period of time as we do today in the weightless state. There also were some doubts at that time as to whether the exposure of the human body to speed and acceleration would be harmful. Some of the differences between air sickness on the one hand, and "space" sickness on the other hand, are based upon the difference between conventional flying and space flight; and they must be considered with respect to the physiological and psychological factors involved.

The moment man travels in any kind of vehicle — train, car, boat or aircraft — he is exposed to motion. We know that individuals differ very markedly as to their motion sensitivity. The chain reaction of physiological events which lead to motion sickness is set off by changes in motion rather than by motion itself; especially if the person is susceptible and unaccustomed to stimulation of our gravireceptoric sense organs. Moreover, inconsistent sensations through the eye, the vestibular organ, and the proprioceptors may produce psychosomatic disturbances when a conflict arises between sensations closely related to the autonomic nervous system. If, on the other hand, the organism is under a heavy stress — for instance during high accelerations — the effect is not motion sickness but injury and collapse. All this can happen during conventional flights.

On the other hand, in space flight the state of zero-gravity will prevail, as already mentioned. In this case changes in motion or acceleration will not occur, but the gravireceptors may be in a state of stimulation, noticeable or subliminal. Moreover, if there is no sensation of motion and acceleration, the gravireceptors of the labyrinth and the peripherally located mechanoreceptors are more probably not stimulated at all. This is what actually happens in the weightless state: Practically all of our subjects reported sensations of rest or "floating"; a few persons observed sensations of motion during the transition phase. This seems to indicate that in the first case the otoliths do not register in spite of the fact that the subject is moving toward the center of the earth with an acceleration of 9.81 m per second, per second; and that in the second case they may discharge impulses at a rate which is characteristic for weightlessness, as SLATER hypothesized already in 1952 [19]. If, then, the individual finds himself in the gravity-free state, no further changes of acceleration or gravity will occur except those elicited by his own voluntary movements. But already BALLINGER has stated — and this was verified by our subjects — that voluntary head movements during weightlessness do not produce untoward effects [21].

This means that the critical phase appears to be the transition from one state into another; and as a matter of fact, we cannot identify the source of the

feelings of unpleasantness and the psychosomatic disturbances reported by some of our subjects very accurately as yet. There is some evidence that the adverse effects are brought about through changes. Hence, we have good reason to assume that persons who can stand the transition into zero-gravity will continue to feel all right during prolonged states of weightlessness. Those cases, moreover, which showed improvement through repeated exposure, indicate that tolerance to the transition phase can be increased by repetition. Since it was shown experimentally by HENRY, BALLINGER and others (1952) that the weightless state itself does not cause disturbances of the circulatory system, longer exposures may not include more hazards than short exposures [20, 21].

The psychological factors also seem to be of importance. According to STEELE (1956), motion sickness is more readily understood in terms of the information handling capacity of the brain; i.e., the effort expended by the individual to remain oriented, instead in terms of overstimulation [22]. Several of our subjects reported sensations of motion and position very different from the actual situation. They also agreed that they were completely disoriented when they closed their eyes and discarded the proprioceptive stimuli. Hence it seems that some of the motion sickness symptoms may be produced by the sensory inconsistencies and the final breakdown of the subject's frame of orientation.

In a similar way, SIMONS (1955) introduced the concept of "mental set for falling" into the discussion of motion sensitivity during space flight [18]. It seems now that some individuals may develop such set more easily than others, whereas certain persons do compensate for noticeable stimulation of the gravireceptors during the weightless state by means of rational reasoning. One of our subjects put it this way: "... I am weightless, hence I cannot fall." If we assume that the psychological factors associated with the experience of weightlessness are subjected to learning, we also may conclude that the individual will adjust better, the more he improves his ability to remain oriented.

The serious functional disturbances observed during our experiments occurred mainly with persons having a relatively low resistance to motion sickness. Patient *C.P.D.*, for instance, was found to be very susceptible to changes in acceleration. He was tested with the EXNER Spiral, and the after-effects of a 30-second exposure were relatively long (28, 37, and 25 seconds). The differences of the after-effects between right and left rotation in the BARANY chair were very pronounced (14.25 vs. 23.0) showing a high sensitivity to labyrinthine stimulation in one direction. He also reported hot and cold feelings after this test at 20 r.p.m. The general diagnosis through the Flight Surgeon was "chronic and severe motion sickness in a predisposed individual."

The other case of high motion sensitivity is Subject *F.N.R.*, who enjoyed the weightless state as an unusual environmental condition but developed the first symptoms of nausea already during the dives. We also saw subject *F.G.H.* coming back from his flight showing severe symptoms of nausea and motion sickness, which incapacitated him for the rest of the day. Although these cases do not permit definite conclusions as to the contribution of sub-gravity to the symptoms of motion sickness, there seems to be enough evidence to assume that persons who are particularly sensitive to stimulation of the gravireceptors will also be inclined to develop autonomic disturbances during weightlessness.

Summing up the discussion we can say that there are considerable differences among personal experience of the weightless state. While the majority of our subjects enjoyed being partly or practically weightless, a few cases reported symptoms of motion sickness, the reasons for which could not be determined as yet. If changes of gravity are the cause, transition from one state into another

will be critical; but no detrimental effects are to be expected in the zero-gravity state. If a hypersensitivity to unusual stimulation of the gravireceptors is the cause, prolonged states of weightlessness may aggravate these symptoms. Upon these premises one can assume that the first group can endure longer periods of sub- and zero-gravity without incapacitating attacks of "space sickness"; whereas the members of the last group will not be fit for space flying at all. This latter percentage does not seem to be alarming, however.

It seems to me that some progress has been made in attacking the problem of human tolerance to weightlessness since 1952, when SLATER presented his paper to the members of the Third International Astronautical Congress [19]. But a lot more remains to be done. The solution of our problem is quite important for the manning of space vehicles in the future. The crew of an artificial satellite, for instance, must live in the weightless state for days or even weeks. Space flight, on the other hand, including shuttle service to a satellite, will involve frequent changes of accelerative forces. Earlier calculations by GAUER and HABER (1950) and recent experiments by PRESTON-THOMAS, EDELBERG, HENRY, MILLER, SALZMAN, and ZUIDEMA (1955) indicate the high accelerations and their pronounced changes necessary to attain the escape velocity [4, 24]. The latter investigators presented evidence that "select crewmen can be expected to assist in the control of such a vehicle during the critical acceleration phases of the flight" [24]. Even if our evidence is by no means as clear cut as theirs, we nevertheless believe that selected crews will also be able to perform efficiently under sub- and zero gravity conditions.

The final word concerns the designer of the future space vehicles. Since physiological difficulties during weightlessness were expected, the introduction of a continuous slight acceleration as a sort of "quasi-gravity" was already mentioned by TSIOLKOVSKII and GANSWINDT at the end of the last century; and some of the modern engineers accepted this proposal as a necessity for their blue-prints. This, of course, is a complication which the designer wants to avoid; for every additional device and every kilogram load — not to speak of room and expenses — is a nuisance in a space craft more than in any conventional type of airplane. If we succed in solving the remaining problems of human tolerance to sub- and zero-gravity, we not only help the future space cadet to perform his job, but also the designer and the engineer by facilitating his task of constructing the hardware for the great venture.

Appendix

Instructions to the Subject on Experiment on Human Tolerance to Sub- and Zero-Gravity

1. This experiment is made to gather information about *your* experience of weightlessness. Read these instructions carefully and follow them through your flight.

2. There will be 4 dives from an altitude of 20,000 to 17,500 feet producing weightlessness for about 15 seconds. Pull the canvas in front of you during the first three dives and direct your attention exclusively to the sensations, feelings, and perceptions of weightlessness. Keep your eyes open during the first dive, have them closed during the second dive; and observe a floating object or your arms during the third one. Find out, how it feels to be weightless. This task requires insight and practice; that is the reason why we fly this maneuver three times.

3. Push the canvas back after the third dive and look outside during the fourth one. Does this make any difference to your perceptions and sensations in the weightless state?

4. There will be a short period of recovery during straight-and-level flying at 20,000 feet. If you are not sure about your experiences or want to try again under a certain condition, let the pilot know. The pilot will repeat the maneuver.

5. If you get motion sick or feel uncomfortable, communicate this to the pilot. He will adjust the temperature and return home. Switch to 100% oxygen.

6. If you feel comfortable, the pilot will fly a series of 3 parabolas, one after the other. This will produce practical weightlessness up to about 30 seconds in each parabola, and a radial acceleration of about 3 g's during each pull-out. Compare how this feels now. Shake your head slowly in the horizontal and vertical plane during the third period of weightlessness. Do you notice any changes in perception or even visual illusions during head movements?

7. If you should feel uncomfortable, direct your attention to exploring the cause. Is the feeling of unpleasantness enhanced during weightlessness or during the pull-out? If you get sick, tell the pilot; he will fly you home.

8. If you feel well and want to try, the pilot will conclude the flight by two slow rolls; one to the right and one to the left. Compare how this feels, and whether visual illusions occur during the maneuver.

9. Please render a written report about your personal experiences and your tolerance during the weightless condition. The more interesting experiences you can report, the better you can help us. If nothing seems of interest to you, sum your experiences up in about 4 or 5 phrases.

10. *Remember:* In a few years, people will have to live and work in sub- and zero-gravity for some hours and even days. Your contribution is essential for the exploration of space.

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THE OXYGEN BELT IN THE PLANETARY SYSTEM

by

Hubertus Strughold

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AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

The Oxygen Belt in the Planetary System

Hubertus Strughold*

Randolph Air Force Base, Texas

The possibility of life on other planets is frequently associated with the presence of oxygen in their atmospheres. This is understandable because for the kind of life that we know, oxygen is the key element that releases the potential chemical energies contained in the foodstuffs, which then appear in the form of heat, movement and other forms of energy. The biochemical reaction which accomplishes this is the biological oxidation in the cells. This biological reaction leads to a breakdown of the food-stuff molecules, down to the smallest possible components like water and carbon dioxide. Consequently, the gain of energy therein is high. Only biological oxidation has made possible the development of living creatures to higher stages.

There is another energy producing biological reaction which takes place without the presence of free oxygen. This is the simple splitting of the foodstuff molecules, a reaction which does not lead to a breakdown into the smallest possible components. The amount of energy gained in this process, also called fermentation, is therefore low, sufficient however for lower organisms. Though free molecular oxygen is not required in this process, oxygen is somehow involved insofar as the respective foodstuff molecules contain oxygen intramolecularly. As we know it, based on carbon as the basic structure atom, life centers around oxygen as the basic energy releasing atom. For this reason the higher organisms require an ample supply of free molecular oxygen from the surrounding environment.

Quadrillions of tons of oxygen are contained in the terrestrial atmosphere and in the oceans. Up to an altitude of 15,000 feet, its concentration is high enough that settlements, even of such oxygen hungry creatures as men, can be found. But how about the oxygen problem on other planets? In order to understand this we must not only consider the planets in their present state of development but also in their former stages during their historical evolution. Well founded theories on the historical development of the earth's atmosphere have recently been advanced by Kuiper,[3] Urey[11] and others. They will serve as a basis for the considerations that follow. We shall begin with the chemistry of the protoatmosphere of the earth.

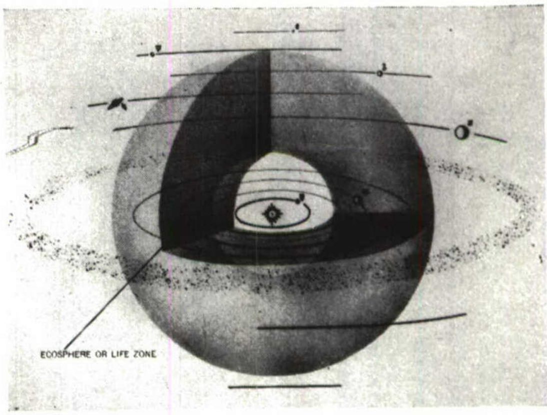

FIG. 3. Ecosphere or Life Zone of the planetary system comprises Venus, Earth, and Mars. Within the ecosphere lie the oxygen, liquid-water, and biotemperature belts—all essential to support life as we know it.

The protoatmosphere of the earth is understood as that gaseous envelope which surrounded our planet during its developmental stage as a protoplanet (Fig. 1). This stage represents the range of time during which the accumulation of cosmic dust and planetesimals into a planetary body was completed or nearly

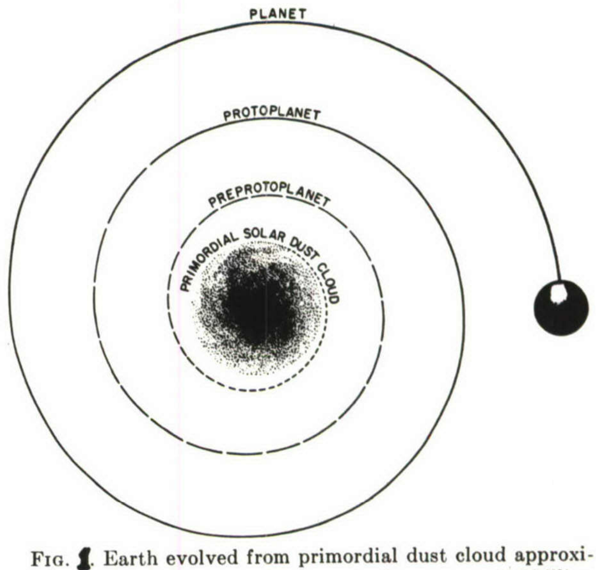

FIG. 1. Earth evolved from primordial dust cloud approximately 5 billion years ago. In its protoplanet stage, 2.5 billion years ago, earth's surface formed into a semisolid or solid crust.

* Chief, Department of Space Medicine, U. S. Air Force School of Aviation Medicine.

completed and the surface was formed into a semisolid or solid crust. It was the transition period from pregeological to geological time—some two and a half billion years ago.

At this primordial stage the earth's atmosphere contained essentially hydrogen and the hydrogen compounds methane (CH_4) and ammonia (NH_3), water vapor and helium. Its chemistry was marked by the predominance of hydrogen. It was a gaseous sphere of reducing and reduced chemicals, which did not deserve the prefix "atmo", i.e., for "breathing." Soon, however, under the influence of ultraviolet of solar radiation a change set in. According to Harteck and Jensen,[1] and Poole[5], by means of photodissociation the water molecules at the border of the protoatmosphere were split into hydrogen and oxygen. The lighter hydrogen escaped into space; the heavier oxygen, however, remained. With the appearance of this initial oxygen, the protoatmosphere attained oxidizing power. Ammonia was oxidized to free nitrogen and water; and methane was oxidized to carbon dioxide and water. Additionally, large amounts of carbon dioxide were injected into the air by volcanic eruptions. In this way the protoatmosphere was enriched more and more by oxidized compounds. With the appearance of chlorophyl, more than one and one-half billion years ago, this change was accelerated by the progress of photosynthesis. The oxygen, thus abundantly produced, oxidized the remaining hydrogen compounds. The excess of oxygen accumulated to rather large amounts, such as are observed in the present day atmosphere. This stock of atmospheric free oxygen amounts to 1.2 quadrillion metric tons.

TABLE I

Main Components of the Terrestrial Protoatmosphere and Atmosphere of the Earth in Their Order of Abundance

Protoatmosphere	H_2	He	Ne	H_2O	NH_3	CH_4	A
Atmosphere	N_2	O_2	H_2O	A	CO_2		

TABLE II

Components of the Planetary Atmospheres

Planet	Most Important Probable Atmospheric Components in Order of Their Abundance				
Pluto	H_2	He	(CH_4)		
Neptune	H_2	He	CH_4	(NH_3)	(H_2O)
Uranus	H_2	He	CH_4	(NH_3)	(H_2O)
Saturn	H_2	He	CH_4	NH_3	(H_2O)
Jupiter	H_2	He	CH_4	NH_3	(H_2O)
Mars	N_2?	A?	CO_2	H_2O	
Earth	N_2	O_2	H_2O	A	CO_2
Venus	N_2?	CO_2			
Mercury	—	—	—		

Such was probably the course of events during the transformation of the protoatmosphere to the present day atmosphere in which we live. About 2 billion years ago hydrogen was predominant in the earth's gaseous envelope as an active chemical agent; today oxygen is the dominant agent. In the hydrogen atmosphere of the remote past, microorganisms such as

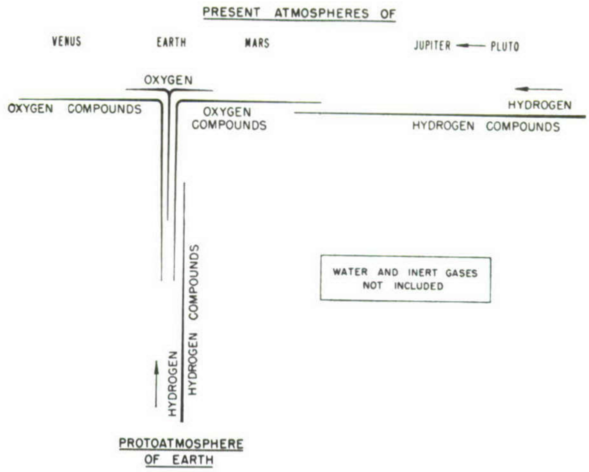

Fig. 2. Photochemical transformation of planetary atmospheres is possible only in a certain distance range from the sun: the farther a planet from the sun, the less transformed its atmosphere.

hydrogen bacteria, methane bacteria, and ammonia bacteria could have found a suitable environment, if some initial oxygen had been already available, but not higher organisms. They are oxygen creatures par excellence. So much about the historical development of the Earth atmosphere.

When we now consider the present day atmospheres of other planets, we find an extremely interesting parallel to what we have just discussed.

Astrophysics teaches us that the atmospheres of the outer planets—Pluto, Uranus, Neptune, Saturn, and Jupiter, consist of hydrogen and the hydrogen compounds (methane and ammonia and frozen water). Mars contains oxidized compounds like carbon dioxide but no free oxygen or only traces of it. Because of its lower gravitational pull, which is only 38 per cent of that of the earth, proto-Mars probably lost its free oxygen into Space. Venus has a completely oxidized atmosphere and also no free oxygen. The higher temperature of proto-Venus, due to its nearness to the Sun, was probably the cause of its oxygen loss. Mercury, the smallest of the planets and the closest to the Sun, could not possibly hold an atmosphere because of its very high temperature and its low gravitational pull.

In considering the evolution of the protoatmosphere of Earth to the present day atmosphere, we see a transformation from a hydrogen and hydrogen compounds containing atmosphere, into an oxygen and oxygen compounds containing atmosphere, caused by the radiation of the Sun. In contrast the planets from Pluto to Jupiter show even today, the original atmospheric chemical components: hydrogen and hydrogen compounds. From Mars to Venus, however, we deal with oxidized atmospheres. Apparently a photochemical transformation of planetary atmospheres is possible only in a certain distance range from the Sun. Thus, we can make the interesting observation: we find the

same course of events when we consider the planetary system from the remote distance from the Sun to its neighborhood, as we find it when considering the evolution of the Earth's atmosphere from the remote past to the near present: a transformation of reduced to oxidized atmospheres (Fig. 2). Chronologically, the atmospheres of the outer planets may all be about the same age as those of the inner planets, but they are apparently younger with regard to their material metabolism as effected by the Sun's radiation. If this is so, then indeed we recognize in the chemical composition of the planetary atmospheres—in their sequence from the outer to the inner planets—a recapitulation of the ontogeny of the earth's atmosphere to use a phrase famous in Paleobiology.

In this paper, however, our interest is concentrated upon the realm of the oxidized atmospheres found on Mars, Earth and Venus. Under these, the Earth is outstanding with its additional rich supply of oxygen. We can call this zone in which planets with oxidized atmospheres are found: the *oxygen belt in the planetary system*. Only in this belt the photochemical transformation of the original planetary atmospheres was possible. Only in this belt, therefore, organisms are conceivable which depend upon oxygen or more generally on oxidation processes. Oxygen, however, is only one important ecological factor. Another is the presence of water in the liquid state. This too is only possible in a certain distance range from the Sun (*"liquid water belt"*).[6] The factor which controls this condition is the temperature. The temperature range which permits water in the liquid state includes also the somewhat smaller temperature range which permits active life (*biotemperature belt*).

All of these three mentioned ecological belts are found in about the same distance range from the Sun. Therefore, we can consider them as parts of a belt which can be best designated with the more general term—the life zone or *"ecosphere"* of the Sun. In this ecosphere in the planetary system the oxygen belt invites our special interest from an astrophysical point of view as well as a biological one. (Fig 3)

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A SIMPLE CLASSIFICATION OF THE PRESENT AND FUTURE STAGES OF MANNED FLIGHT

by

Hubertus Strughold

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RANDOLPH AIR FORCE BASE, TEXAS

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A Simple Classification of the Present and Future Stages of Manned Flight

BY H. STRUGHOLD, M.D., PH.D.

WHENEVER great inventions or discoveries are made, there is public concern with their potentialities and the length of time required for their full realization. This has been notably true in the application of the rocket principle of propulsion to flight. Rocket flight and space flight symbolize trips to the moon or to Mars. As long as these trips do not materialize, in the public view there is no such thing as space flight. This all-or-nothing attitude is often found in conversations, in radio and television programs, and in print.

It is true that the development of the rocket principle of propulsion is an achievement of revolutionary significance. Yet its complete exploitation will probably follow the pattern of a gradual evolution. The stages of this evolution can be understood best if we examine three factors: (1) the physiological and mechanical properties of the environment; (2) the speeds attained by rockets; (3) and distances they travel over and away from the earth.

ENVIRONMENT

It is well known that the border between the atmosphere and space, in meteorological and astrophysical terms, lies at an altitude of about 600 miles. As an environment for the flyer and the vehicle, however, the atmosphere shows conditions typical of space at much lower altitudes. We encounter within our atmosphere, beginning at 50,000 feet, a region which becomes increasingly *space-equivanent* with regard to one or more of the conditions important for manned flight. These conditions are anoxia (50,000 feet), the boiling point of body fluids (63,000 feet), the necessity for a sealed cabin (80,000 feet), meteors (75 miles), and the darkness of space (100 miles).[9]

Above 120 miles we find space-equivalent conditions in almost all respects. The atmospheric region from 50,000 feet (about 10 miles) up to 120 miles may be considered partially space-equivalent, and the region above 120 miles totally *space-equivalent,* if we ignore certain environmental effects which are caused by the solid body of the earth, its magnetic field, and its own and reflected radiation[8] (Fig. 1). Above the 120 mile level, the atmosphere is unrecognizable in manned flight. It is imperceptible to the flyer, although for the astronomer it exists up to 600 miles.

This being true, the rocket powered plane which has carried man to 90,000 feet and the rockets which have carried animals up to 36 miles,[4] have flown in a region which is space-equivalent to a high degree. A two-stage rocket,

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From the U. S. Air Force School of Aviation Medicine, Randolph AFB, Texas. Dr. Strughold is head of the Department of Space Medicine.

Presented on March 21, 1955, at the luncheon during the annual meeting of the Space Medicine Association, Washington, D. C.

the WAC corporal mounted on the nose of a V-2, which attained an altitude of 250 miles, was flying under conditions of total space-equivalence even though for a few minutes only. Do not these achievements in very high altitude flying, justify the statement that we have already reached the era of space flight? From the standpoint of the environment we are at present in the partial space-equivalent phase of manned flight.

SPEED

Just as we find levels that are characteristic in the environment around the earth, so too do we find certain characteristic points in the factor of speed. They also mark distinctive stages in the development of flight (Fig. 2).

The first of these is the speed of sound (760 m.p.h. at sea level). The present record in the supersonic speed range exceeds Mach 2. In the higher range of Mach 3 or 4, in horizontal flight, centrifugal forces begin to counteract gravitation to an increasingly noticeable degree. This brings on the phenomenon of decreased weight or subgravity. Theoretically, at about 18,000 m.p.h. or 5 miles per second, in a horizontal flight the state of weightlessness, or the gravity-free state, is finally reached. This speed of 5 miles per second or 8 km. per second, where centrifugal force equals the gravitational pull of the earth, is known as the orbital, or better, circular velocity. It is the speed which will enable a craft to circle about the earth in a fixed circular orbit like an artificial satellite. At 7 miles per second or 11 km. per second, the craft breaks away from the earth's gravitational pull and escapes into the depths of interplanetary space. It is called the escape velocity.

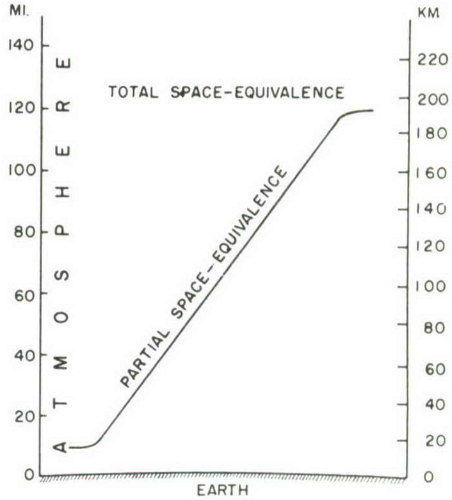

Fig. 1. The space-equivalent regions within the earth's atmosphere.

The highest speed so far attained in a two stage rocket (the WAC Corporal mounted on a V-2) is 1.4 miles per second. This is 30 per cent of the orbital and 20 per cent of the escape velocity. This is where we stand today with regard to speed. The three-stage rocket[1,5] or the atomic rocket[2,7] may bring in the remaining percentage.

DISTANCES

The various stages of flight can also be classified by the factor of the distance they cover. The craft may fly from one point on the globe to another point on the globe, in a certain distance around the globe, or far away from the globe into space.

If we combine the factors of environment, speed and distance with their characteristic levels into one

picture, we see an evolutionary course in the development of manned flight that looks somewhat as follows: The long distance flights of today take us

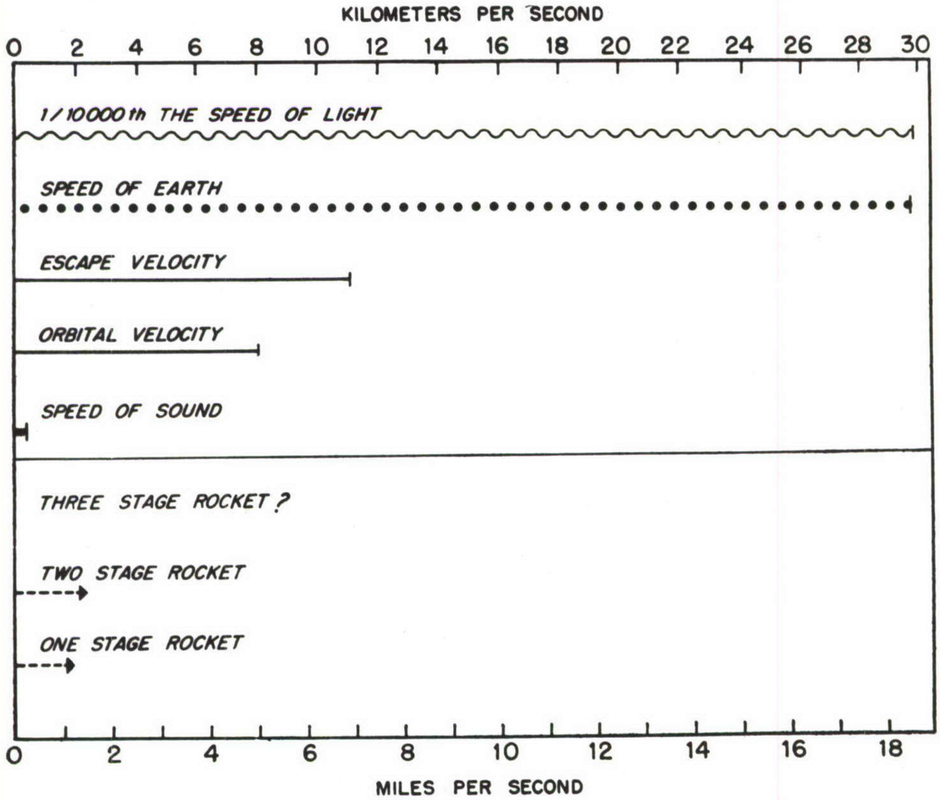

Fig. 2. Speed records in rocket flight compared to speed of sound, orbital velocity and escape velocity.

at subsonic speed, under normal gravitational conditions, in pressurized cabins through the lower regions of the atmosphere from one point on the globe to another distant point on the globe, across a number of time zones and/or across zones of different seasons in a single day. These are *global atmospheric flights*. This epoch in flying began when Lindberg crossed the Atlantic Ocean in 1927.

We are now on the threshold of the next stage. Rocket powered planes will take us at supersonic speed under subgravitational conditions and in sealed cabins through the space-equivalent regions of the atmosphere from one point on the globe to another even more distant point in a matter of hours.[3] Still bound to the earth, they will fall into the category of *global space-equivalent flight*. The precursors of this long distance *space-equivalent* space flight are seen in the short distance, short time flights of rocket powered planes and unmanned rockets of today. They can be termed *local space-equivalent flight*.

As soon as the orbital velocity (5 miles per second) is reached, flights of long duration around the globe in a satellite orbit under conditions of zero gravity and in an environment equivalent to space will become possible. But these craft still will operate within the gravitational hold of the earth and will remain within the earth's vicinity. This eventual stage may be called *circumplanetary space flight.*

The next step will follow as the escape velocity (7 miles per second) is reached. When, one day, a manned rocket leaves the earth, attains this speed and moves freely in space, then we will have arrived at *interplanetary space flight* or what we may now call "space travel."[1,5,6]

This classification (Table I) gives us, I believe, a clearly defined and realistic picture of the stage at which we stand today and of the possibilities we may expect in the future. At present we are actually in the first phase of space flight, the phase defined as *global space-equivalent flight.* Solution of the medical problems in this stage is, therefore, of immediate concern to the physiologist, the engineer, and the flyer. Incidentally, most of the medical problems involved in the final stage (space travel) are encountered in the stage of *global space-equivalent flight.*

This step by step approach to the possibilities of rocket-powered flight by human beings is perhaps more stimulating, and more fruitful for research and development, than the all-or-nothing attitude displayed by those who constantly gaze upon remote celestial bodies like the moon or Mars with a kind of space fascination. The psychological power of attraction of these objects as the final goal, however, must not be underestimated. They are extremely valuable as a background stimulus for our efforts towards advancement of human flight.

TABLE I. CLASSIFICATION OF DEVELOPMENTAL STAGES IN MANNED FLIGHT

	I Global Atmospheric Flight	II Global Space-equivalent Flight	III Circumplanetary Space Flight	IV Interplanetary Space Travel
Distance	Geographic Dimensions	Geographic Dimensions	Vicinity of Earth	Interplanetary Dimensions
Environment	Lower Atmosphere	Space-equivalent Regions of the Atmosphere	Circumplanetary Space	Interplanetary Space
Speed	Sub- and Supersonic Speed	Supersonic Speed	Orbital Velocity	Escape Velocity
Gravitational Condition	Normal Gravitation (1 g)	Subgravity	Zero Gravity	Zero Gravity

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MEDICAL PROBLEMS INVOLVED IN ORBITAL SPACE FLIGHT

by

Hubertus Strughold

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SCHOOL OF AVIATION MEDICINE, USAF
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RANDOLPH AIR FORCE BASE, TEXAS

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Medical Problems Involved in Orbital Space Flight

HUBERTUS STRUGHOLD[1]

School of Aviation Medicine, U.S.A.F., Randolph Air Force Base, Texas

After analyzing the various kinds of space operations that might be expected in the near or remote future (space equivalent flight, circumplanetary space flight, and interplanetary space travel), the second phase—circumplanetary space flight or orbital space flight—is chosen as a platform for the discussion of some of the most important medical problems involved in space operations. First, the state of weightlessness is discussed with regard to its effect upon the general well-being of the occupants of a satellite vehicle and in regard to its sensomotor effects. In connection herewith, the optical situation is considered with regard to the properties of the environment and the visual appearance of the light sources. Furthermore, physiological day-night cycling is discussed in an environment where there is no natural day and night. And finally some problems involved in human engineering of the space cabin concerning pressurization, supply of oxygen and removal of carbon dioxide, photosynthetic gas exchange, and the event of sudden decompression of the cabin are discussed. Some of these problems are presently under study in an experimental space cabin simulator.

Introduction

FOR about seven years space medicine—a branch of aviation medicine—has been studying the human factors involved in flights into the upper atmosphere and beyond, into space. There are various phases of this kind of flight depending upon the physical and physiological characteristics of the environment, the speed of the vehicle, and upon the destination of the flight.

The first phase of space operations that we can expect in the immediate future will be the long distance flights at supersonic and hypersonic speeds through the space equivalent regions of the higher and upper atmosphere. These flights will be the logical development of the present-day long distance atmospheric flights on a global scale and can justly be called global or long distance space equivalent flights. With regard to motion dynamics, part of the time the vehicle exhibits airplane status and part of the time projectile status. We are now at the threshold of this first phase of space flight, namely, global space equivalent flight (10, 27).[2]

The second phase in the development of human space flight will have been achieved as soon as the orbital velocity of about 17,500 mph has been reached. This speed, which enables a vehicle to circle for a longer period of time or even permanently around the earth in an orbit, gives the vehicle satellite status. This is circumplanetary space flight or, more specifically, circumterrestrial space flight (4).

As soon as the escape velocity of 25,000 mph has been reached, the vehicle will have attained spaceship status; this will be the final phase of space flight and can truly be called interplanetary space travel (34).

It is my purpose in this paper to discuss the medical problems involved in the second phase of space operations, namely, that of circumplanetary space flight or satellite flight. This is full-fledged space flight in its simplest form: full-fledged, because all of the strange environmental and motion conditions associated with space flight are encountered; in its simplest form, because the vehicle's movement is uniform with regard to speed and trajectory. Circumplanetary space flight, therefore, is an especially suitable example for discussion of the fundamental medical problems confronted in space flight. As for its technical side, see (4, 9, 11, 21, 24, 25, 26, 31, and 34).

The first step in the direction of this phase of space flight is the instrumented unmanned satellite, such as the one to be launched in 1957 (18); but we shall take a step further and assume, for the purpose of our discussion, an instrumented manned satellite. We shall not, however, discuss how this vehicle arrives at its orbit and the medical (acceleration) problems involved—which are not insurmountable—but rather we shall presume to be at the stage where the vehicle has already reached a certain orbit and has attained satellite status. But, I should like to add at this point, this paper in no way directly relates to the scientific satellite program which is presently under way.

The speed required to attain satellite status is about 18,000 mph near sea level. The denser regions of the atmosphere would prohibit this speed because of air resistance and friction heat. At about 120 miles or 200 km, however, the air is without noticeable effect in both respects (5). This aerodynamic and aerothermodynamic border of the atmosphere can therefore be designated by the more general term, flight effective limit or final functional limit of the atmosphere. The actual material border of the atmosphere, however, reaches into the area of 600 miles or 1000 km from where we enter, through a 600-mile-wide spray zone, into interplanetary space. But it must be emphasized that even above the final functional border the atmospheric environment is space equivalent in practically every respect. It is here that the laws of aerodynamics lose their meaning and those of astrodynamics (Romick) become fully effective, rather than at the material limit of the atmosphere.

Above 120 miles, therefore, the nearest satellite orbit is conceivable. The orbital speed required at this level is, roughly, 17,500 mph and the period of revolution is about 88 min. Naturally, with increasing altitude, the orbital velocity decreases and the period of revolution increases.

For our medical discussion, let us assume the 2-hr orbit slightly above 1000 miles, as chosen by W. von Braun for his space platform. At this altitude we are in the exosphere, far beyond the final functional limit and also beyond the material limit of the atmosphere. The particle density is about 10 per cm^3. In the 2-hr orbit the orbital velocity is about 15,800 mph.

Weightlessness

Characteristic of orbital flight is the fact that the gravitational pull of the earth and the centrifugal forces caused by the vehicle's inertia are balanced, which means that the vehicle and its occupants are in the state of weightlessness or zero gravity. This is the first of the medical problems that I would like to discuss. There are two sides to this problem: (a) the general medical aspect regarding the well-being of the occupants, and (b) the sensory physiological aspect concerning perception of position of the body in space and sensomotor control of the movement of the body and its parts.

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[1] Chief, Department of Space Medicine. Mem. ARS.

[2] Numbers in parentheses indicate References at end of paper.

So far, experiments on man—to study the effect of zero gravity (16)—have been carried out only up to 30 sec in parabolic flight maneuvers in jet planes. The experiments of E. R. Ballinger (2) in Wright Field Aero-Medical Laboratory in 1952, those of Harold von Beckh in Buenos Aires (3) in 1953, and most recently those of S. J. Gerathewohl in Randolph Field, Texas, do not as a rule indicate a general disturbance in the automatic nervous system which controls respiration and circulation. J. P. Henry et al. (17) in their recordings on monkeys in a V-2 and an Aerobee during a 3-min period of zero gravity, found no evidence of a significant disturbance of the cardiovascular or respiratory system. So far, we have no proof that there would be any difference during a longer period of time, such as would be found in a satellite. A possible shift in blood pressure, due to the absence of hydrostatic pressure in the blood vessels, might be easily regulated by the presso-regulators of the arterial system. The whole problem boils down to the question of the possibility of adaptation to the state of zero gravity. Such adaptation seems to be a possibility. At this point, I should like to add that a manned artificial satellite is the only means of bringing about a final solution of this entire problem, because it alone offers the possibility of experiencing the gravity-free state for periods of days, weeks, and months, not too far from the earth.

As to the second, or the sensory aspect of the gravity-free state, this can be said: we have several sense organs, or specific nerve endings, that serve as gravi-receptors, such as the centrally located otolith organ and the receptors of the pressure sense distributed peripherally over the entire skin (about 20 per cm^2); specific nerve endings in the muscles, the so-called muscle spindles; and, finally, specific nerve endings in the connective tissue, the Pacinian corpuscles. They all belong to the category of mechano-receptors; these receptors have an exteroceptive function insofar as they react to external forces and inform us about the outer world. One such external force is the gravitational pull of the earth. They also have an enteroceptive or a proprioceptive function insofar as they inform us about the tension conditions in the skin, the muscles, and the connective tissue. They play, therefore, an important role in the senso-motor control of the movements of the whole body as well as of its parts. In the case of the vestibular apparatus and the presso-receptors of the skin, the exteroceptive function is more pronounced; in the other mechano-receptors, the proprioceptive function is dominant.

In the gravity-free state the exteroceptive or the gravi-receptive function of the mechano-receptors is eliminated; the proprioceptive function, however, is not. For this reason, a man making a high dive from a diving board is able to perform a variety of acrobatic jumps quite skillfully, although he is in a gravity-free state throughout the dive. In a gravity-free state the absent gravi-receptive (exteroceptive) function of the mechano-receptors is substituted by the exteroceptive sensory organ par excellence: the photoreceptors or, in other words, the eyes. When in the gravity-free state, as in a satellite, the eyes will be the only sense organ that informs the occupants of their position in space. This brings us to the problem of vision in space.

Visual Problems

Of what kind are the light sources that confront us in space? Direct sunlight and starlight are first; we are also confronted by indirect sunlight coming from the earth, reflected by the continents, the oceans, and especially by the clouds. Moreover, some of the indirect sunlight is scattered from the denser layers of the atmosphere back into space. Finally, we have indirect sunlight reflected from the moon's surface. But there is no skylight and this is the factor that makes the visual conditions so strange in the regions where satellites are conceivable. Skylight is sunlight scattered in all directions by the air molecules. Because the short wave part of the visible spectrum is especially affected, the scattering produces the diffuse blue daylight in the denser regions of the atmosphere, as it is observed from the earth's surface. Against this rather bright skylight, during the daytime the stars fade into invisibility. With increasing rarefication of the air molecules in higher altitudes, scattering of light diminishes gradually and ceases at about 80 to 100 miles (15). This is the optical functional border between atmosphere and space or the visual space equivalent level within the atmosphere. It is the dividing line between atmospheric optics and space optics. Beyond this level the sky is permanently dark. The extra-atmospheric sky luminance is only 10^{-5} mL as compared with that of 500 mL, the average value in the lower atmosphere. But the sun is visible in its full brilliance against the dark sky, except of course when the satellite moves through the shadow of the earth. The stars are also visible all the time, and when its position allows, the moon can be seen in full brightness together with the sun. Because of the lack of skylight in space, the contrast between light and dark is a dominant feature. Everything that is exposed to sunlight appears in full brightness and vivid color, and everything else is in the darkness of shadow. The extra-atmospheric illumination is around 13,500 ft-c compared with 10,000 ft-c at the earth's surface. Light and shadow dominate the scenery, comparable to the light and shadow effects such as those produced on the stage for the magician. This strange photoscotic condition poses physiological problems in the field of contrast vision and retinal adaptation (7, 15). And the strange distribution of the light sources, sun, stars, and the indirect sunlight from the earth and moon, is of special interest from the standpoint of orientation in space (6).

At this point I should like to make a comparison with an environment that is, so to speak, the extreme opposite of that found in space, namely, the deep sea. But there are also some similarities, according to the well-known proverb, "les extremes se touchent."

W. Beebe observed in his "bathysphere" that the light intensity in the sea decreases rapidly with increasing depths. At a depth of 1600 ft, light is completely absent in the Atlantic Ocean. In these regions we find fish with luminous organs and telescopic cylindrical eyes. At depths of about 10,000 ft there are fish with only vestigial eyes. These deep sea fish rely almost entirely on the mechano-sensory system of their skin to sense the environment. This represents an extreme contrast to the situation that will be experienced by man under space conditions. In the darkness of the deep sea, where the photo-receptors are out of function, the position and movement of the fish is controlled solely by the gravi-receptors; in the darkness of deep space and under the gravitational conditions of orbital space flight where the gravi-receptive function of the mechano-receptors is eliminated, orientation of man depends entirely upon the photo-receptors or upon vision.

We do not know whether man can adjust to purely optical orientation in space. Fish can be trained for an optical orientation in their environment. Several years ago it was found by E. von Holst that when an aquarium in a dark room was covered with a black plate and the light penetrated through the glass bottom, some of the fish will swim upside down, and will look for fresh air at the bottom which is lighted and will swim to the dark surface of the water when they want to rest.

In orbital space flight, the sun, the stars, and the earth and moon are the optical footholds for the visual orientation in space. The observation of the sun, however, poses an important medical problem. The brilliant radiance of the sun in its original intensity, while not affected by atmospheric absorption and scattering, represents a hazard to the eyes. A much shorter time of exposure is sufficient to cause a retinal burn, such as that known to the ophthalmologist, as it occurs occasionally when someone observes a solar eclipse through an insufficiently smoked glass. The result of such a so-called "eclipse blindness" is a scotoma or a blind spot in the visual

field. Outside of the atmosphere, the danger of such a retinal injury by direct solar light is much greater, and from an artificial satellite the sun should be observed only through glass with very high absorptive power.

In connection with the optical conditions found in the space equivalent regions of the atmosphere beyond 120 miles and in interplanetary space, I should like to touch upon a physiological problem that has never been discussed in space medical papers. It is the problem of maintenance of an adequate physiological day-night cycle for the occupants of a space vehicle.

Physiological Day-Night Cycling

In orbital space flight, the concept of natural night loses its meaning and must be replaced by that which night really is, namely, the shadow of the earth.

The shadow or umbra of the earth tapers down in the form of a cone 859,000 miles or 1,385,000 km deep into interplanetary space. Travelling through the greatest width of this sunless dark cone would take our assumed satellite about 50 min. During the remaining part of the revolution (about 70 min) the vehicle is exposed to the sun and surrounded by darkness at the same time, as described earlier. Such are the optical conditions if the satellite orbit passes through the earth's shadow.

Many different orbital planes, however, are conceivable; in every case at a distance of about 1000 miles an adequate ambient physical day-night cycle is absent because the day-night or, more precisely, the sunlight-shadow cycle is only 2 hr. Therefore, we must create and maintain an artificial day-night cycle within the satellite to meet the physiological requirements of the occupants. For, adequate diurnal cycling is of great importance to the health and efficiency of man. In fact we are physiologically so strongly adapted or so bound to a day-night cycle, manifested in rest or sleep and wakefulness or activity, that it must be regarded as a biological law. To ignore this law, after a week or so, would lead to a complete nervous breakdown (19, 33).

How can an adequate day-night cycle be achieved for the occupants of an artificial satellite? For them, the night must be induced in a special night compartment or by a device covering the eyes. The question is posed as to the time pattern of such an artificial day-night period.

In this regard, reference is made to the important basic experiments carried out in the Mammoth Cave in Kentucky, 1940, by N. Kleitmann, Professor of Physiology at the University of Chicago (19). Dr. Kleitmann spent two months in this cave with several co-workers, under artificially regulated day-night cycles of different lengths. The result of these experiments showed that man can adapt himself to a diurnal cycle only in the range from 18 to 28 hr. Within this range the temperature curve of the body follows the various cycles. When a cycle shorter than 18 hr or longer than 28 hrs was introduced, no adaptation was possible and the temperature curve returned to its normal cycle of 24 hr.

This gives us the clue for solving the problem of diurnal cycling in a manned satellite. If we choose a minimum day-night cycle of 18 hr, dividing it into 8 hr for sleep, 2 hr for recreation, and 8 hr for duty, that would be a reasonable solution. Or, if a 24-hr day-night cycle is selected, the best plan for a subdivision of this cycle would be 8 hr for sleep, 8 hr for rest and recreation, and 8 hr for duty. This presupposes that the crew will be large enough to be subdivided into three groups. In the case of an artificial 18- or 20-hr day-night cycle, a two-group crew would be sufficient for a manned satellite operation.

Human Engineering of Space Cabin

We may assume that the metabolic rate of an occupant of an artificial satellite during his duty hours, is about the same as that of an individual on earth during moderate work; the total metabolism during a 24-hr period, including sleep and recreation, would then be on the order of 2500 cal for a 70-kg man. This brings us to the respiratory requirements for the satellite crew or, more generally speaking, to the climatization of the cabin (1, 13, 22, 7). The cabin in a satellite must, of course, be completely closed—a sealed cabin in which an adequate atmosphere is artificially created and controlled. It must be emphasized, however, that such a type of cabin is required even down to the atmospheric region of 70,000 to 80,000 ft.

One of the vital tasks in the climatization of the sealed cabin is the solution of the oxygen problem for respiration.

From the afore-mentioned metabolic rate of 2500 cal per man per day, we can calculate the amount of oxygen required by one man per day. The thermal equivalent of 1 l of oxygen is 4.85 cal under normal nutritional conditions. This means that the biological production of 1 cal requires 206 cm^3 of oxygen. Consequently, the total amount of oxygen consumed per man per 24 hr is roughly 500 l or 0.7 kg. This amounts to 58 kg of oxygen per man for 1000 satellite revolutions that take place in 83 days in our assumed orbit at the 1000-mile altitude, or 348 kg O_2 for a crew of six. Replacement of the consumed oxygen from the storage tanks must be controlled in such a way that the oxygen pressure does not fall below 100 mm Hg. This is about the minimum permissible limit for comfort and efficiency; it should not surpass the permissible maximum of about 350 mm Hg because O_2 concentrations above this level are toxic (8). This shows that we can tolerate a rather wide variation in oxygen pressure (from 100 to 350 mm Hg), which facilitates considerably the oxygen problem in space flight.

Whereas oxygen is consumed in the metabolic processes of the body cells, carbon dioxide is produced in the same process and exhaled. Under normal nutritional conditions, the ratio between exhaled carbon dioxide and consumed oxygen, the so-called respiratory quotient, is 0.85. In our example, one man produces 425 l of carbon dioxide or 0.837 kg per day or 70 kg per 1000 satellite revolutions. This would be 420 kg for a crew of six. Carbon dioxide in concentrations above 3 vol per cent is toxic; the permissible limit for a longer period of time lies at about 1 vol per cent under standard barometric pressure and temperature conditions, or at about 8 mm Hg. The removal of the excess carbon dioxide in the sealed cabin vehicle, which can be achieved by certain chemicals or in a physical way is, therefore, just as vital as the maintenance of an adequate oxygen pressure.

Since the consumed oxygen appears again in bound form, namely, within the carbon dioxide of the expired air, it has been suggested to try to regain the oxygen from the carbon dioxide, in this way eliminating a toxic gas and at the same time facilitating the problem of oxygen supply.

A natural method accomplishing this is known to us in the process of photosynthesis, found in chlorophyl-bearing plants. Photosynthesis is the reverse process of respiration as a comparison of their reaction formulas shows

$$\text{Respiration: } C_6H_{12}O_6 + O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy}$$

$$\text{Photosynthesis: } 6CO_2 + 6H_2O + \text{Light Energy} \rightarrow C_6H_{12}O_6 + O_2$$

In respiration or biological oxidation, oxygen is consumed and carbon dioxide and water are produced. This process requires several so-called respiratory enzymes. In photosynthesis, oxygen is produced and carbon dioxide and water are consumed. This process requires the presence of chlorophyl as an enzyme.

In special studies sponsored by the U.S.A.F. School of Aviation Medicine, it has been found by J. Myers, head of the Department of Algal Physiology, University of Texas, Austin (23), that 2.3 kg fresh weight of a certain alga—the alga chlorella pyrenoidosa—with regard to gas metabolism, under optimal conditions, is sufficient to support one man. This means that this mass of algae consumes as much carbon

dioxide and produces as much oxygen per time unit as one man produces carbon dioxide and consumes oxygen during the same period of time. Both, therefore, could live together and support each other with regard to the respective respiratory and photosynthetic requirements in a symbiotic-like relationship in a closed system for a considerable length of time.

Plants like the alga chlorella are especially suitable as photosynthetic gas exchangers. They are small round bodies about the size of red blood cells and are dispersed in a nutritional solution. These primitive plants are perfect photosynthetic machines, since they have no specific organs nor various functions like the higher plants. Their only function is to build up carbohydrates and to produce oxygen photosynthetically. Primitive plants of this type appeared on this planet $1^1/_2$ billion years ago. And they might have been responsible for an early buildup of an initial stock of oxygen in the primitive atmosphere or proto-atmosphere of the natural satellite of the sun, namely, the earth. But the difficulties in the use of such photosynthetic gas exchangers lie in the volume and weight of the device, in the arrangement of and in the power requirement for illumination. As for the latter, solar energy may be the answer. For flights of short duration, however, we certainly shall never resort to a biological gas exchanger. For flights over weeks and months it might be different. Perhaps some day we shall have a type of photosynthesis that can utilize infrared; or the efforts that have been made for a number of years in order to achieve artificial photosynthesis may one day be successful.

In the sealed cabin also, the water vapor given off—in amounts of from 50 to 80 gram per man per hour through respiration and perspiration under comfortable temperature conditions by the occupants—must be kept within the comfort limits that range between 30 and 50 per cent relative humidity. And, finally, the barometric pressure should be kept at levels corresponding to that found near sea level and up to 9000 ft. In this respect, however, the physiologist could make concessions to the engineer, who for structural reasons would probably desire a lower pressure differential between the cabin's air and the surrounding near vacuum. From the physiological point of view, a minimal barometric pressure corresponding to an altitude of about 15,000 ft would be acceptable.

The multitude of factors involved in the climatization of the sealed cabin requires a complex instrumentation for automatic control. The School of Aviation Medicine, U.S.A.F., Randolph Air Force Base, Texas, now has an experimental sealed chamber (Fig. 1) in which we can study the changes of the atmospheric conditions caused by the presence of the occupants, and the means to control these factors. This space cabin simulator can also serve as an indoctrination chamber in handling the situation in case the automatic controls fail or the cabin develops a leak.

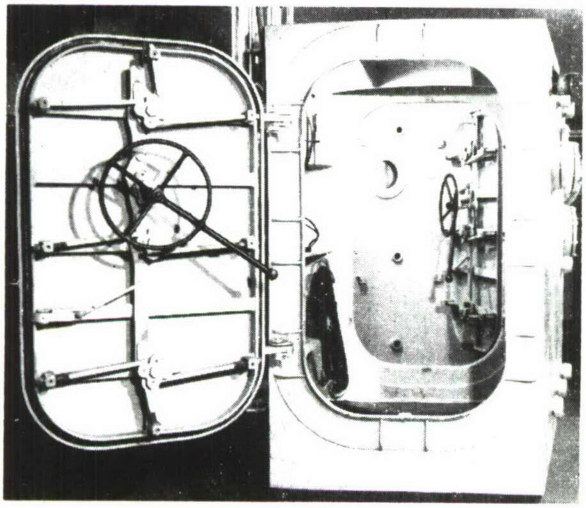

Fig. 1 The space cabin simulator of the School of Aviation Medicine, U.S.A.F., Randolph Air Force Base, Texas

Decompression Event of the Space Cabin

With this point we touch upon the Achilles' heel of the sealed cabin vehicle. One of the causes of a leak might be a collison with a meteor (20), a probability which is very remote; however, the occupants of a satellite vehicle must be prepared for such an event, even though meteor bumpers or screens—suggested by F. Whipple (35) and others—might offer effective protection.

In the lower atmosphere, the time rate of decompression of the pressurized cabin is governed by four factors: the volume of the cabin, the size of the hole, the barometric pressure within the cabin, and the barometric pressure of the ambient atmosphere. In a satellite vehicle, the last factor is practically zero, which means that under other equal conditions the decompression will be faster and more violent. In any event, the crew must know that a drop in oxygen pressure to 100 mm Hg will affect their efficiency, as mentioned earlier, and at an oxygen pressure of 60 mm Hg the situation will become critical and dangerous. Before this critical level is reached, the source of the leak must be sealed; otherwise, the crew would face the whole physiological sequence of decreasing air pressure effects.

Conclusion

These are some of the medical problems encountered in orbital space flight. I have not touched upon the radiation and temperature problem (12, 28, 29, 30) which has been discussed in the paper of David G. Simons (30).

All of the space medical problems discussed so far are also encountered in transfer orbits to other celestial bodies, that is, in interplanetary space travel. Some of them will be faced also, more or less, during a certain portion of space equivalent flights, that is, in long distance flights at hypersonic speed through the space equivalent regions of the atmosphere, as previously defined. But we find them, so to speak, in classical form in nearly circular orbital space flight.

I have chosen, therefore, this phase of space operations for this paper because it offers an ideal platform for the discussion of the problems of space medicine in general, and provides an up-to-date picture of some of the progress made in this fascinating branch of aviation medicine.

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THE TRUE NATURE OF THE BOILING OF BODY FLUIDS IN SPACE

by

Julian E. Ward

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The True Nature of the Boiling of Body Fluids in Space

By Captain Julian E. Ward, USAF (MC)

THE boiling of body fluids at low barometric pressures and in free space has become a subject of such renewed interest that it is desirable to outline the fundamental factors delineating this problem. Misconceptions about this medical problem should not arise either among professional workers or in the mind of the general public. In popular periodicals and to some extent in the scientific literature, there has arisen the concept of the fixed altitude boundary at 63,000 feet for the boiling of body fluids. Certain instantaneous death was thought to lie just inches above this line for the unprotected flyer unfortunate enough to be decompressed there. It is the purpose of this report to point out the fluidity of such a boundary, the derivation of which arises from a number of highly inconstant variables.

HISTORICAL

The concept of achieving the boiling point of a liquid by either raising its temperature or by lowering the ambient pressure has been known since the time of Boyle's original studies and Dalton's subsequent investigations of vapor pressure. Felix Hoppe-Seyler[12] in 1857 made the first systematic observations of the boiling of body fluids of frogs, birds and mammals under low ambient pressures, but many of his observations are confused because of the effect of hypoxia which was poorly understood at that time. From the standpoint of aviation medicine, the first description of such a phenomenon occurring in animal body fluids was made by Armstrong[1] in 1938. Blood from the jugular vein and carotid artery of intact animals was shunted into a small glass cell where observations of bubble formation and water vaporization were made. Armstrong also observed that between 40,000 and 70,000 feet there was a very rapid rate of water-loss from the body of the living animal. He believed that this phenomenon was probably due to the fact that the vaporization rate of body fluids at constant (body) temperature is proportional to the decrease of barometric pressure. Since 1938, a number of reports have been published concerning certain aspects of this phenomenon.[3,13,15,18] In a recent report Beischer[3] studied dehydration of frogs, cockroaches and worms at 5 mm. Hg. pressure for periods of from one to six hours, following which the organisms were rehydrated and remained viable.

TERMINOLOGY

The use of the word *boil* in reference to this physiopathologic condition is unfortunate. Both the transitive

From the Department of Space Medicine, U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas.

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and intransitive forms of the verb *boil* either directly indicate or imply the addition of heat to a liquid to bring it to the boiling point. The term *space ebullism** is suggested to describe the phenomenon of vaporization of body fluids at body temperatures in space, because the word ebullism does not connote the addition of heat to produce vapor. The word ebullism is used in a medical syndrome sense to describe the clinical events which occur in living tissue. It is to be differentiated from the word *ebullition* which applies to this chemical-physical phenomenon occurring in inanimate objects. The term ebullism covers all of the signs and symptoms observed as the result of boiling of body fluids at very high altitudes. Heat loss, down to the actual freezing point of body tissues, is the terminal phase of the ebullism syndrome. Ebullism may occur at an ambient pressure which equals the vapor pressure of the liquid without formation of bubbles, as pointed out by Hitchcock and Kemph.[11] However, bubble formation is absent only during a slow rate of decrease in barometric pressure and in a liquid virtually free of dissolved gas bubbles. These circumstances will not exist in a decompression in space, because gas bubbles will be dissolved in all body fluids and the decompression will likely be most rapid or even explosive, if it occurs at all.

GENERAL BOILING PHENOMENON

Vaporization of a liquid occurs when the vapor pressure of that liquid at a specified absolute temperature equals the ambient pressure in contact with the liquid. Actually molecules of the liquid leave the liquid surface in a vapor state even at low temperatures and at high pressures with vapor-saturated air above the liquid but, because of the dynamic equilibrium present (i.e., the return to the liquid surface of equal numbers of molecules from the vapor state), the material remains as a liquid.

At equilibrium the number of molecules per unit volume of saturated vapor is less than in an equal volume of liquid. This difference, however, decreases as the critical temperature is approached. Before a molecule can attain the vapor state it must overcome the attraction exerted by the other molecules in the liquid phase, i.e., the forces of cohesion. Therefore, the average potential energy of the molecules in the vapor phase is greater than the mean potential energy of the molecules in liquid phase. Expressed mathematically:[6]

$$\frac{n_v}{n_L} = e^{-L_i/RT}$$

where n_v = number of molecules per unit volume of vapor, n_L = number of molecules per unit volume of liquid, L_i = internal latent heat of vaporization per mole, R = gas law constant and T = absolute temperature. As the temperature is raised and the ratio n_v/n_L increases (n_L does not vary appreciably with temperature), the molecular concentration in the gas phase, and hence the vapor pressure, increases. Consideration must be given the factors which influence the vapor pressure of liquids and the natural laws which govern these factors, as

*From Latin ebullire, meaning "to bubble out, or to boil up."

well as the criteria influencing the way in which boiling may be manifested.

In the laboratory, the change in vapor pressure of a "pure" liquid is a function of the temperatures involved, the specific volumes of the molecules in both liquid and vapor states, and the heat of vaporization for that liquid at the particular temperature considered. Broadly speaking, the specific volume of the liquid or vapor is a general statement of the cohesiveness of the molecules at a particular temperature and pressure, whereas the heat of vaporization is an expression of the energy required to convert a given number of molecules of the liquid into vapor at a specified temperature and pressure. This relationship may be expressed mathematically by the Clapeyron equation.*

$$dp/dT = \frac{L}{T(V_2 - V_1)}*$$

where dp/dT is the rate of vapor pressure change with respect to temperature, L is the molar heat of vaporization, T = absolute temperature, V_2 = the volume of 1 mole in the vapor state, and V_1 = the volume of 1 mole in the liquid state. For example, water at 37° C. has a heat of vaporization of 575.8 calories per gram, and the volumes occupied by 1 gram of water and vapor are 1.007 ml and 22.780 ml, respectively. Therefore, at 37° C. the rate of change of vapor pressure of water is 2.553 mm. Hg per degree (1 calorie = 41.29 ml-atm.). At "body temperature," then, the rate of change of vapor pressure is quite small when compared to the value obtained for water at its ordinary boiling point of 100° C. Under the latter conditions, there is a 27.1 mm. Hg per degree centigrade rate of vapor pressure change, a tenfold increase.

In other words, whereas slight variation in temperature at relatively high "cooking" temperatures has a marked influence upon vapor pressure, at body temperatures the variation of vapor pressure with slight temperature changes is small, but still significant. Assuming a temperature gradient over the entire body including skin of, for example, 15° C. (37° C. to 22° C.), this would account for a difference in water vapor pressure of about 27 mm. Hg. between various areas on the basis of temperature alone. Neglecting for the moment all other (quite important) factors, such differences would be relatively rapidly stabilized, however, when one considers that for each gram of water vaporized, about 575 calories of heat would be lost. Such evaporation would tend to occur at a greater rate in the warmest portions of the body gradient since vapor pressure would be highest there, and the warmest areas would then be cooled progressively down to the level of the coolest portions of the body, at which point the vapor pressures would be the same for the entire body with no

*A modification of this expression is the Clausius-Clapeyron equation, in which the specific volume of the liquid (V_1) is considered negligible compared to the specific volume of the vapor (V_2). And since by the basic gas laws PV = RT (R = gas law constant) then RT/P may be substituted and the equation becomes $\frac{dp}{dT} = \frac{Lp}{RT^2}$.

Integration evolves the form

$$\ln p = \frac{-L}{RT} + C,$$

where C = the integration constant, allowing reasonably accurate calculation of the absolute vapor pressure.

temperature gradient, and generalized vaporization at equal rates would proceed. If only 5 per cent of the body weight of an 80 kilogram man is lost through evaporation, more than 2,000 kilo calories of heat would be dissipated. If this heat loss occurred over a period of minutes or seconds, multiple areas of freezing would occur (normally 5-7000 [redacted] K cal/day are dissipated). Because human body tissue is a poor heat-conducting medium, such theoretical heat transfer would be limited in some measure. In space the vaporization and heat loss will continue until generalized freezing occurs, when the vapor pressure of the solid water will be the same as the liquid water. In time, the vapor pressure of the frozen liquids and tissue will continue to fall as more heat loss occurs by radiation.

Non-Volatile Solutes.—Another important influence upon vapor pressures of liquids is the presence of another substance within the liquid system. The nonvolatile solute affects the ability of the solution to vaporize, by decreasing the tendency of molecules to escape from solution into vapor form. The degree to which a nonvolatile dissolved substance will affect the vapor pressure of the solvent is more nearly a mole function rather than weight function of the solute and solvent. Raoult's law is the basic formula which correlates the concentration of the solute with the vapor pressure of the solvent and is expressed mathematically by

$$p = Np^1$$

where p is the vapor pressure of the solution, i.e., the partial pressure of the solvent in the solution, p^1 is the vapor pressure of the pure solvent and N is the mole fraction of the solute. This formula is quite accurate for dilute solutions (below 1 molal). With rearrangement of terms

$$\frac{p^1 - p}{p^1} = \frac{n^2}{n_1 + n_2} = N_2$$

where n_1 = no. of moles of solvent, n_2 = no. of moles of solute and N_2 = mole fraction of solute.

Although it is usually not convenient to determine molality of a solution directly, a close approximation is indirectly provided where the freezing point constant* (Molal depression constant) of the solvent and the freezing point of the solution are known. For example, the freezing point constant for water is 1.86° C. and the freezing point of serum is normally about —0.56° C. Then the molal concentration of human blood serum is about 0.56/1.86 = 0.3 molal. Therefore, on the basis of the nonvolatile solutes in serum alone we would theoretically expect that the vapor pressure would be slightly below (0.25 mm. Hg. depression) that of water at 37° C., or about 46.75 mm. Hg.

Mole for mole, protein polymers have much less effect than a dissociated salt upon vapor pressure depression of a solution. If a long molecule in solution moves in segments, its vapor pressure and osmotic pressure can be assumed to be affected by the effective mole fraction and not the actual mole fraction. Therefore the more molecules of the protein going to make

*The freezing point constant is $K_f = \frac{RT^2M}{L_f \times 1000}$: where R = 1.987, T = 273.1°, where M = molecular weight of fluid; L_f = heat of fusion.

up the polymer chain, the less effect will be exerted upon vapor pressure depression.[16] This may be expressed by

$$\frac{p^1 - p}{p^1} = N'_2 = \frac{n'_2}{n_1 + n'_2}$$

where N'_2 = effective solute mole fraction, n_1 = no. of molecules of solvent, n'_2 = effective number of molecules of solute.

Volatile Solutes.—Water is the most important volatile liquid component of the body, constituting about 70 per cent of the total weight. However, certain other substances found within the body in relatively small quantities also may be volatilized, including certain organic acids and alcohols and, in larger amounts, hydrochloric acid in the stomach (about 0.4 per cent concentration as secreted). The behavior of such binary systems is complex in that they may exhibit so-called "maximum" or "minimum" boiling point curves.[5] Because the slight importance of binary systems of solutions in the body does not warrant more discussion, suffice to state that with gastric contents under extremely low ambient pressures we would expect vaporization of the gastric juices to evolve virtually pure water until a specific high concentration of HCl is achieved. Such a highly concentrated acid residue is theoretically capable of producing gastric tissue injury. After achieving this "maximum," the evolved vapor would constantly contain the same concentration.

Colloids.—The most important stabilizing factors in a colloidal solution are the state of hydration and/or the zeta potential, i.e., the electrical charge of the particles. Lyophobic colloid suspensions depend only upon the repelling charge for separation. However, lyophilic colloids maintain a film of adsorbed liquid on their surface (and sometimes also a zeta potential) to maintain dispersion in the colloidal state. When this film is lost, if no repelling charge exists, coagulation occurs. It has been noted in an interesting pilot study reported by Guest[8] that there may be a basic change in the zeta potential on the red cells and plasma colloids following exposure of blood samples to 30.4 mm. Hg. ambient pressure. Although adsorptive pressures tending to maintain the solvent film may be tremendous, e.g., in the order of hundreds or thousands of atmospheres per square inch, evaporation can still occur quite readily, for these expressions of adsorptive pressure reflect only the extremely small size of the colloid particle (the hemoglobin molecules ranges between 10^{-4} and 10^{-7} [illegible]) and the consequent enormous surface area involved in a colloid solution. Because of some of the peculiar characteristics of water, hydration is one of degree, ranging from mechanical entanglement to the closely adhered water molecules of "saturated water" in an intense electrostatic field. The probable primary effect upon vapor pressure of proteins in colloidal suspension with a crystalloid is an alteration of the amount of water present to act as solvent for the crystalloid, acting to slightly depress the vapor pressure of the water solvent. This effect would in some measure balance the effective mole fraction effect of protein polymers, tending to make

Raoult's law more nearly correct for human serum.

It is well established that lyophilization followed by rehydration may substantially alter the biochemical and physiologic properties of certain body proteins. In an episode of space ebullism it would be expected that only certain body proteins would undergo this severe degree of dehydration before death of the organism would ensue. Specifically, only proteins found in the body integument would have the opportunity to be subjected to this rapid drying action prior to death. Therefore, one might postulate that if an episode of ebullism occurred in space and if rapid enough emergency measures were taken and the individual recovered, it is conceivable that some functions of skin proteins might be temporarily altered, e.g., vitamin D synthesis.

ANATOMICAL CONSIDERATIONS

Because of certain local factors, various regions of the body display a more marked effect upon the water vapor tension. In 1933 Christie and Loomis[4] accurately measured the vapor pressure of the water in normal respiratory alveolar air and found that this value was about 2 mm. Hg. lower than the accepted value of 47 mm. Hg. This observation was partially explained by: (1) the lack of equilibrium between blood and alveolar air; (2) the difference in the osmotic pressure of the blood and water; and (3) a lung temperature 0.24° C. lower than the measured rectal temperature. It is also of interest that these authors found that the alveolar water vapor pressure inexplicably dropped as much as 9 mm. Hg. during a ten to fifteen-second period of hyperventilation.

Because vaporization is essentially a "surface" (gas-liquid interface) phenomenon, the greatest water loss will occur on integumental surfaces. At altitudes far below the 63,000 foot level, the presence of reduced barometric pressure increases both evaporative and perspiration rates at a given body temperature (mechanism unknown). At lower altitudes this produces a beneficial effect so that by augmenting the body heat loss, the thermal tolerance of man at altitude is increased. Although this surface type of water vaporization will be entirely devoid of visible vapor or bubble formation, it will probably account for the major fraction of vapor formation. Decompression to ambient pressures below the pressure of water vaporization will produce most active ebullism on moist integumental surfaces, particularly the mucous membranes of the mouth, anus, and ocular conjunctivae. Likewise the moist surfaces of the gastrointestinal tract will provide a copious source of water vapor, which, added to the relative gas expansion of trapped gases already within the bowel, may produce gastrointestinal injury.

Any area of the body which operates under a relative negative pressure differential with respect to ambient pressures may be expected to evolve water vapor almost immediately after extremely low pressure decompression. For example, vigorous inspiration movements with the glottis firmly closed may lower the intrapulmonic pressure 30 to 80 mm. Hg. below atmospheric pressure. During normal inspiration, there is about a 4 mm.

Hg. pressure drop in intrathoracic pressure, below atmospheric pressure. It has been noted[9] that intrathoracic water vapor begins to form at 51 mm. Hg. ambient pressure in the dog. Such a "vapothorax"[11] may rapidly collapse the lungs and cause serious circulatory embarrassment.

Because of a relatively constant intraocular tension in man of from 20 to 25 mm. Hg., it may be expected that water vapor formation in the anterior and posterior ocular chambers will begin at about the same time as intravascular arteriolar and capillary vaporization. Sufficient vapor could form rapidly enough to seriously interfere with the ocular refractive system and cause severe visual impairment. This localization of ebullism could occur at altitudes above 84,000 feet.

Circulatory Pressures.—The systemic pressure gradient spectrum, which spans from the left ventricle throughout the circulatory tree and continues in a decreasing slope until the right ventricle is reached, should be considered from the standpoint of the initial impact of circulatory ebullism. In resting man, the pressures in the great veins at the entrance to the heart may range in the order of from 0 to 3 mm. Hg., and at the venous ends of the capillaries from 6 to 18 mm. Hg. pressures are encountered (Fig. 1). Of course this gradient may be increased by an increased rate of right heart output, by arteriolar dilatation accompanied by venoconstruction, and by increased negative intrathoracic pressure established by elastic recoil of the lungs. On the arterial side of the tree, a progressive gradient occurs with pressures below 40 mm. Hg. in the terminal arteries and arterioles up to a mean aortic pressure of about 100 mm. Hg. Therefore, we may assume that in the circulatory tree following decom-

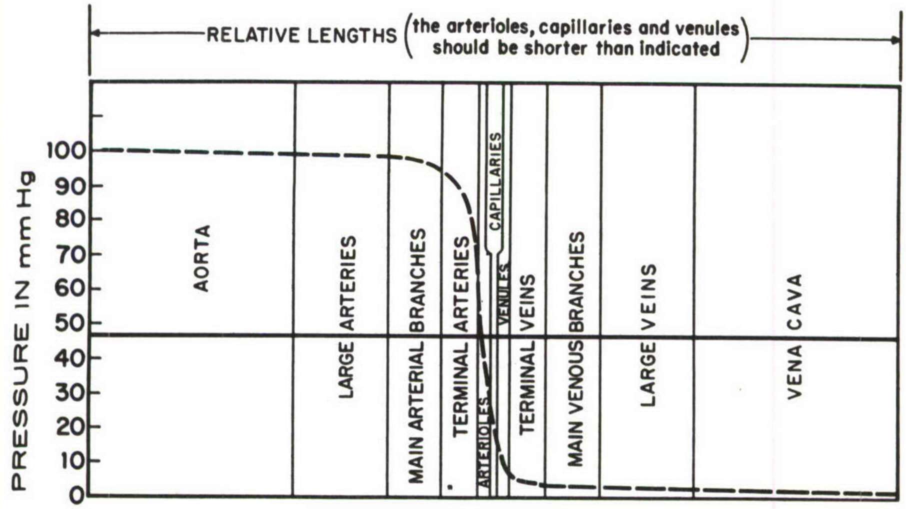

Fig. 1. Schematic diagram of mean blood pressure in different blood vessels during circulation with the superimposed water vapor pressure line (modified from Green[7]).

pression to ambient pressures well below 47 mm. Hg, vaporization of the blood will begin most vigorously at the entrance of the great veins to the heart and rapidly progress in a retrograde fashion down to tissue level, producing in effect an acute right heart failure. Because of the rapid dilatation of the peripheral arterioles which will occur as a compensatory mechanism for ischemia from generalized hypoxia and from the ischemia engendered by the right heart failure, arterial pressures will rapidly fall below the vapor pressure of water, allowing further retrograde vaporization up the arterial side of the vascular bed, and finally gas bubble formation within the left heart chambers. Such conjecture has been partially confirmed by Hitchcock and Kemph,[11] who detected gas in the heart (cardiac vapor lock) in 50 per cent of dog subjects after explosive decompression to ambient pressures of 30 mm. Hg. Gas bubbles were noted to appear first in the right, then in the left ventricles. Cardiac vapor lock and circulatory arrest occured well within fifteen seconds following decompression in this series.

It has been shown that the assumption of a uniform, constant temperature of blood and tissues is false. Temperatures as low as 21.5° C. and 31.1° C. for the radial and brachial arteries, respectively, have been reported,[2] without the subject being unduly cold. A common central temperature within the main central vessels is found only when an individual has been maintained at rest for a considerable interval in a warm room and a steady state has been achieved. The temperature gradient within the blood vessels is quite variable, being dependent upon the skin temperature distal to the vessel, the degree of peripheral vasoconstriction or vasodilatation, the efficiency of anastomoses, and other related factors. Because of the small rate of change of vapor pressure with respect to temperature, within the body temperature range, and counterbalancing hydrostatic pressures, the actual sequential progression of intravascular ebullism will not be essentially changed from that described.

Because confusion might arise on this point, for practical reasons it is desirable to indicate the actual ambient barometric pressure at which vaporization of a liquid will occur in a particular body area. For this purpose the use of the term *effective ebullism pressure* is suggested to take into consideration all factors which would tend to produce ebullism at a particular body site, and the corollary terminology, *specific altitude of ebullism,* indicating the actual altitude at which ebullism occurs for a stated anatomic location. As an example, the theoretical effective ebullism pressure and specific altitude of ebullism for blood in the median basilic vein are derived:

"Effective Ebullism Pressure"

Vapor Pressure of Water at 37°C.	47.07 mm Hg
Specific Altitude of Ebullism of Water at 37°C.	63,000.00 feet
Vapor Pressure of Water at 30°C*	31.82 mm Hg
Vapor Pressure of Blood Serum at 30°C.	**31.50 mm Hg
Venous Pressure at Median Basilic Vein	** 6.00 mm Hg
Effective Ebullism Pressure at Median Basilic Vein	25.50 mm Hg
Specific Altitude of Ebullism at Median Basilic Vein	76,000.00 feet

*Temperatures of this magnitude encountered in median basilic vein with room temperature 21°C. dry bulb, 16°C wet bulb.

**Approximate values within range normally encountered.

Weightlessness.—Our present knowledge concerning the effects of the zero-gravity state upon circulation has been derived from brief periods of weightlessness in flight. However, from animal manned rocket studies by Henry and his associates,[10] there is an indication that a fall in systolic and diastolic pressures may occur, possibly as a reaction of the cardiovascular system to short exposures to the gravity free state. Actually hydrostatic pressures *per se* will not exist since the fluids are weightless; cardiac circulatory pressures are basically tension pressures. The only effect of a constantly lower vascular pressure would be that intravascular vaporization will proceed much more violently and rapidly in free space than in a similar vacuum produced within an earthbound low pressure chamber. It is possible that on prolonged exposure to zero-gravity, compensatory mechanisms of vascular-pressor receptors will maintain relatively normal vascular tensions.

Evolution of Dissolved Gases.—It is not within the realm of this paper to reconsider the evolution of carbon dioxide and oxygen from the blood and tissues under low barometric pressures except as this affects the release of water vapor. Clinical observation of animal subjects at low pressures has been confused by release of oxygen at about 60 mm. Hg. and carbon dioxide at about 40 mm. Hg. ambient pressures. Without gas analysis it is impossible to determine empirically the composition of the gases released at a particular altitude. Evolution of these gases is a function of their respective dissociation curves, temperature, pH, elastic and hydrostatic pressures, as well as the ambient barometric pressures. These gases affect water vapor release in that they provide a nucleus for the formation of vapor, bubbles, presenting a gaseous-liquid interphase at which liquid vaporization can proceed. For this reason space ebullism, as an acute phenomenon, will manifest extensive tissue and vascular bubbling. The actual physics of physiologic bubble formation is quite complex and has been thoroughly studied by Harvey and his associates.[9]

Tissue Tensions.—One major factor limiting the degree of swelling and expansion of tissues is their elasticity and the rigidity of the enclosing structures. Vapor formation within the tissues of the cranial vault and within bone marrow is markedly limited. Similarly, in all enclosed body tissues, the degree of ebullism will be governed by the tissue elasticity. Kemph, Beman and Hitchcock[14] measured the subcutaneous pressure in dogs sixty seconds after explosive decompression from 740 to 25 mm. Hg., and found a 34 mm. Hg. differential pressure (59 mm. Hg. absolute pressure). The differential pressure is greater than the fluid vapor pressure by the pressures exerted by the evolved nitrogen, carbon dioxide and oxygen. Therefore, we may expect vaporization to proceed until the tissue tensions equal the differential tissue pressure, or until tissue rupture occurs.

CLINICAL IMPLICATIONS

The space flight surgeon and space flyer must understand the process of space ebullism in order to prevent it

from becoming something other than a theoretical medical curiosity.

The 63,000 feet altitude level should not be considered a "functional boundary" above which total space equivalence[19] for this particular condition exists. In a sense, altitudes above 60,000 feet should be considered as variably but progressively space equivalent for ebullism because the severity and rate of progression of this pathologic process will be determined by the actual ambient pressure and the duration of exposure. As has been pointed out, vaporization of body fluids via the skin begins at ground level and the rate of water vaporization at a particular body temperature increases with decreasing ambient barometric pressures. At approximately 50 mm. Hg. (61,500 feet) intrathoracic water vapor may form. However, during a vigorous "negative" Valsalva maneuver it is theoretically possible for intrathoracic water vaporization to occur at altitudes as low as 43,500 feet although recondensation would immediately occur on relaxation. Most body fluids can be expected to begin vigorous vaporization from 63,000 to 63,500 feet (this small difference is accounted for by the effect of solutes in body fluids) up to 67,000 feet (this larger span is accounted for by body temperature gradients). Within this same altitude range, tissue and intravascular ebullism will begin in the venous circuit, producing acute right heart failure. Simultaneously mental disorientation and ocular involvement may occur. Death will supervene by circulatory or respiratory failure.

Explosive decompression above 150,000 feet may terminate in death within a few seconds because of the extremely high rate of water vaporization. On the other hand, at lower altitudes the survival time will be considerably longer. Hornberger[13] was explosively decompressed to 62,300 feet for ten seconds before unconsciousness from hypoxia ensued and no visible evidence of water vapor formation (particularly gas bubbles) was seen.

At present, there is only one conceivable way in which survival from this condition could occur at altitudes above 100,000 feet. If the automatic (C-1 assembly) triggering device of the Air Force partial pressure suit[17] should fail following explosive decompression above 100,000 feet, the flyer would probably have less than seven seconds in which to manually activate his capstans and breathing pressure. At altitudes around 65,000 feet the time of useful consciousness will be primarily determined by the rapid onset of hypoxia in from ten to twelve seconds. Above this altitude, this vital time will be proportionately reduced by the ebullism phenomenon.

SUMMARY

Recent increasing aeromedical interest has been directed toward the physiologic problems encountered in space equivalent flight. In the literature, numerous references have been made to the fact that water maintained at 37°C will boil at 63,000 feet altitude and therefore body fluids also may be expected to boil at this level. There is no fixed altitude boundary for the boiling of body fluids; the exact altitude at which any particular fluid will boil is dependent upon a number of highly in-

constant variables. The term "ebullism" is introduced to describe the phenomenon of vaporization of body fluids at low atmospheric pressures and at body temperatures, thereby avoiding the use of the word "boiling" to describe a medical syndrome.

The general phenomenon of boiling liquids is discussed with particular emphasis on the factors influencing the vapor pressure of fluids, including the effects of temperature, volatile and nonvolatile solutes, and polymerized and colloidal suspensions as encountered in the body fluids. The relationships between hydrostatic and tension pressures, gravity free state, bubble formation, anatomic sites and the ebullism syndrome are discussed. Clinical implications derived from all theoretical considerations are discussed from the viewpoint of the space flyer and the space flight surgeon.

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SENSOMOTOR PERFORMANCE DURING WEIGHTLESSNESS: Eye-Hand Coordination

by

Siegfried S. Gerathewohl

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Sensomotor Performance During Weightlessness

Eye-Hand Coordination

By Siegfried J. Gerathewohl, Ph.D., Hubertus Strughold, M.D., Ph.D., and Major Herbert D. Stallings, USAF

PILOT experiments during parabola flights clearly indicated that the sensomotor performance of human subjects is affected during exposure to subgravity and zero-gravity states.[3] Similar observations were previously reported by von Beckh using a cross-drawing test during the weightless condition.[5] The object of our experiments was to study systematically the effects of changes of acceleration and gravity upon eye-hand coordination. Moreover, it was intended to investigate how well subjects adjust to the various conditions of gravity after repeated practices of the task. Because it has been shown in earlier experiments that the effects of weightlessness on neuromuscular coordination are not very dramatic, an experimental technique was chosen which permitted comparisons among three sets of results obtained during normal, increased, and decreased gravitational forces.[1,2,4]

METHOD

The pilot experiments referred to above seemed to demonstrate that the eye-hand coordination of the subject was impaired during post-acceleration weightlessness.[5] Hence, subgravity and practical weightlessness for a minimum period of ten seconds were produced by vertical dives from an altitude of 20,000 feet to 17,500 feet in a T-33A aircraft powered by a J-33A-35 engine of 4,600 pounds thrust.

The eye-hand coordination test consisted of a simple psychomotor task of aiming at and hitting the center of a test chart with a metal stylus. The chart consisted of a rectangular piece of cardboard 8½ by 11½ inches, with a bull's-eye marked center surrounded by six concentric circles each 1 cm. apart. Corrugated cardboard was used as background of the test chart so that each hit could be identified properly. The chart was attached to the instrument panel in the rear seat of the cockpit. When the shoulder harness was locked, the subject could just reach it with the 7½-inch stylus in his hand. He was instructed to aim at the center of the chart with his arm bent so that the rear end of the stylus barely touched his oxygen mask, and then try to hit the bull's-eye with one fast movement. Aiming and hitting the target was practiced with each subject in the laboratory, and then in the airplane on the ground before each flight.

The test was done under three different flying conditions and accelerations or forces of gravity, respective-

From the Department of Space Medicine, U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas.

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ly: (1) During straight-and-level flight at normal gravity; (2) during the dive at reduced gravity or practical weightlessness; and (3) during the pull-out from a dive at an acceleration of 3 *g*. The method of operation for obtaining the desired flight path was standardized as follows:

1. The best starting altitude for our experiments was found to be 20,000 feet. At this altitude, the maneuver could be flown combining minimum turbulence with maximum performance and safety.
2. Weightlessness was obtained by first flying straight-and-level and then bringing the aircraft in a steep dive until zero-gravity was indicated on the accelerometer. The engine power was reduced gradually to 75 per cent rpm in order to maintain the weightless state. Before an indicated airspeed of .8 Mach was reached, a smooth pull-out was begun in order to prevent the craft passing its speed limit and avoiding strong radial acceleration during recovery.
3. Increased gravity was produced by putting the aircraft in a slight dive until an airspeed of about 350 knots was obtained at an altitude of 17,500 feet. The following pull-out yielded a radial acceleration of 3 *g* for a period of about four to five seconds.

The pilot, who could observe the subject in his rearview mirror, also acted as experimenter during the flight. He announced the beginning and the end of the particular gravitational state, and told the subject when to change the test chart. The experimental design described below is a compromise forced by economy in subjects and flights, and the complexity of the interrelationship of the three gravitational conditions on the same test subject.

There were three experimental conditions, namely, 1 *g*, zero-*g*, and 3 *g*. The order of these conditions was balanced according to a Latin square. Each subject of our experimental group participated in at least three flights. During each flight, he repeated the test six times under the respective experimental condition. During each test and exposure to the prevailing gravitational force, he aimed and hit the target one time with his best hand, using a new chart for each test. Thus, a set of six charts was employed at each flight, and each chart showed one hit mark only at the end of the test. This procedure served to reduce the effect of transfer from one hit to the next during the same experimental condition.

In order to minimize flight-to-flight transfer, the subject practiced once before take-off. Furthermore, the flight schedule was arranged in such a way that each subject flew his mission at the same time of day on the same week-day for three consecutive weeks.

SUBJECTS

Eleven subjects volunteered for the experiment, but only eight completed the test under the three experimental conditions. It must be mentioned here that an experiment on stress was conducted by the Department of Pathology of the School of Aviation Medicine, using the same subjects and flight pattern in conjunction with our tests. For this experiment, the subjects underwent repeated blood and urine tests prior and subsequent to each individual flight. For our experiment, not only motivation and skill, but also flying experience may be of some importance. The flying experience of our subjects, who included

a pilot and a flight surgeon, ranged from zero to more than 1,500 hours. All subjects were examined before the experiment and found to be healthy and qualified for flying.

RESULTS

The test results of the seven subjects used for the evaluation of our data are given in Figure 1. In this figure, all the hits obtained under the three experimental conditions are superimposed on one test chart. The hits obtained during increased acceleration are shown as black dots, those obtained during normal gravitational conditions by X's, and the hits scored during weightlessness are represented by open circles. The hits are dispersed predominantly in the vertical direction, and are particularly crowded around the center. Furthermore, the majority of the hits scored during weightlessness are clustered in the upper half, and those made during increased weight in the lower half of the chart. The marks of the straight-and-level test are distributed rather randomly around the bull's-eye. This indicates a particular tendency of aiming and hitting which seems to be associated with the condition of increased or decreased weight.

For the numerical evaluation of the results, two measures were employed: (1) the absolute distance of a hit from the center of the chart; and (2) the tendency of a hit to be displaced either downward or upward. This latter tendency was measured as the distance of a hit from the horizontal center line of the chart; and it was designated as minus when the hit was below, and plus when the hit was above the line. The mean values of the measurements for the up-or-down tendency are represented by the three heavy horizontal lines in Figure 1.

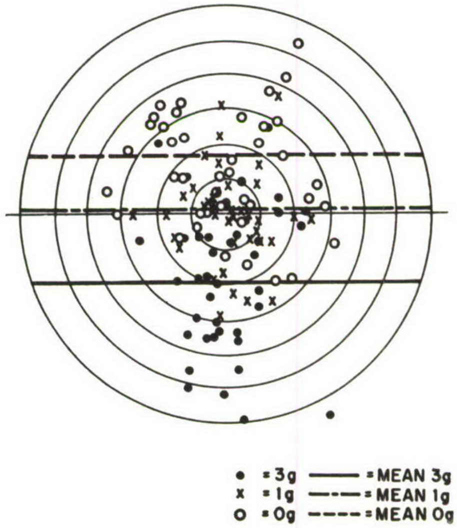

Fig. 1. Total number of hits superimposed on one test-chart. The hits obtained during 3 *g* conditions are shown as black dots, those during 1 *g* as X's and those during zero *g* as open circles. The horizontal lines represent the respective means.

For the sake of clarity, the hits are plotted in a somewhat different fashion in Figure 2. Here, the hits obtained from the experimental group under 3 *g* conditions are plotted on the left, those under normal conditions in the center, and those under subgravity conditions on the right side of the graph. The mean of each cluster is indicated again by the heavy horizontal lines which show the differences between the results of the three experimental conditions very clearly. Moreover, the heavy circle in each of the three charts represents the mean value of the absolute deviation of the hits from the center of the bull's-eye. It appears by this repre-

sentation that the absolute mean deviation obtained under conditions of increased or decreased weight is considerably larger than that observed during normal gravity.

in turn are larger than the 3 g deviations. By comparing the means of the absolute values we find that in thirteen out of the fourteen possible paired comparisons the zero g and the

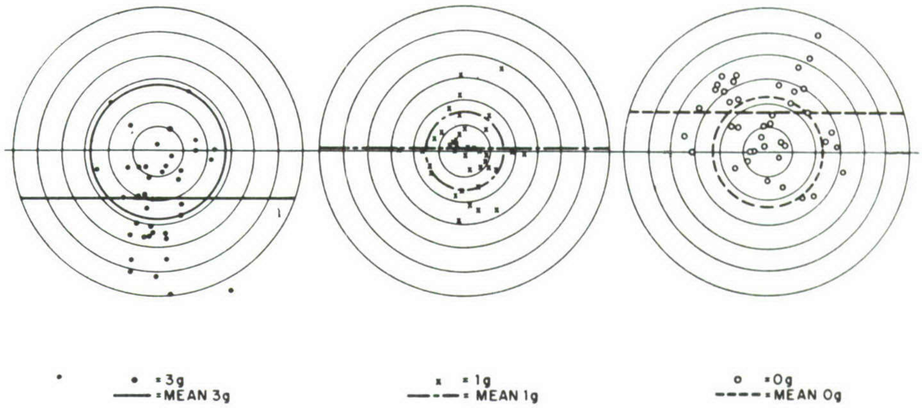

Fig. 2. The hits obtained under 3 g conditions (left), 1 g (center), and zero g (right). The horizontal lines represent the respective mean.

TABLE I. MEAN VALUES OF SIX HITS FOR ALL MEMBERS OF THE EXPERIMENTAL GROUP

Subject	Absolute Deviation*			Vertical Deviation*			Order of Flight		
	0 g	1 g	3 g	0 g	1 g	3 g	0	1	3
1	6.4	21.1	39.5	4.2	—6.4	32.0	1	2	3
1	24.7	19.8	22.9	—18.8	—0.3	17.4	1	2	3
2	31.7	19.0	23.7	21.1	1.6	—17.8	3	1	2
3	26.4	14.6	34.5	7.9	2.3	—32.8	2	3	1
4	11.7	15.2	22.4	8.8	0.3	—13.0	1	3	2
5	19.3	16.8	24.7	16.1	0.6	— 7.5	2	1	3
6	22.8	16.2	29.7	10.2	—5.3	—19.0	3	2	1
7	18.8	12.8	21.2	1.0	—5.2	—16.9	1	2	3
8	28.0	17.5	35.7	18.2	2.0	—29.7	2	1	3

*The figures represent the absolute deviation from the center and the vertical deviation in millimeters.

Table I gives the means of the absolute and the vertical deviations in millimeters, and the order in which the subjects were exposed to the three experimental conditions. With the exception of the first subject, the means of the vertical deviation in the first Latin square show the same trend: The zero g deviations are algebraically larger than the 1 g deviations, which 3 g values are larger than the 1 g means. In addition, we see that six of the seven 3 g means are larger than the means of the zero g condition.

It must be mentioned that subject 1 differed so strikingly from the rest of the group that we had some reason to disqualify him from our evaluation. Since subject 7 had the same

flight pattern as subject 1, some of the statistical analyses of the data were based on subjects 7, 2, 3, 4, 5, and 6, by substituting subject 7 for 1 into the Latin squares.

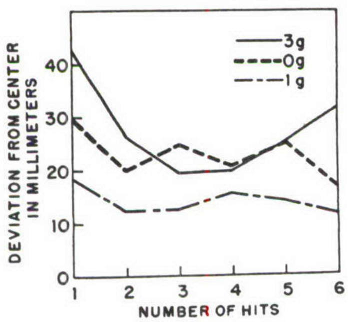

Fig. 3. Absolute deviation of the hits from the center of the bull's-eye. The curves for the weightless state (dashed line) and for 1 g condition (dashed-dotted line) show slight improvement during the six trials.

If subject 1 is retained, the analysis of variance does not yield significant differences for the three conditions of weight; but the differences among individual performance are beyond doubt. When subject 7 is substituted, the differences among the three conditions of gravity are significant at the 1 percent level of confidence. These results therefore suggest that the subject's performance of the aiming task is moderately disturbed by increased or decreased gravity.

Finally, the rate of adjustment to our experimental conditions must be mentioned. The values of the absolute deviation from the center of the bull's-eye are plotted in Figure 3. In this graph, the means of the group are plotted over the consecutive six hits during one flight. The results show that learning takes place under 1 g and zero g conditions. Figure 4 shows the adaptation of the subject to the state of weightlessness only when the up-and-down deviations from the horizontal center-line are graphically represented for our three experimental conditions. The values above the abscissa are the positive means, those below the abscissa the negative means of the group. While the curve for the 1 g condition fluctuates at random, and the curve for the 3 g condition does not show a definite tendency toward the center line, the curve for the zero g condition indicates a steady improvement. Hence, we may conclude that the subjects learn noticeably on subsequent trials. In this aiming test, the subject simply compensated for the deviation caused by increased or decreased weight of the arm by aiming either higher or lower than under normal conditions; and it can be seen that compensation through practice was better for decreased than for increased weight. Thus, the subject reached about the same accuracy

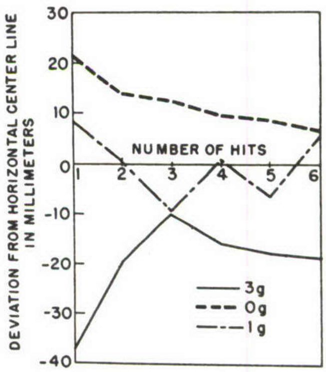

Fig. 4. Vertical deviation of the hits from center of chart. Only the curve for weightlessness (dashed line) shows a steady improvement during the six trials.

after six trials during weightlessness as he did within the random fluctuation of performance under normal conditions.

SUMMARY AND CONCLUSIONS

A series of experiments was performed to study sensomotor performance and adaptation during the weightless condition. Subgravity and zero-gravity states were produced by flying dives at high altitudes in a T-33A type aircraft. The results of a simple aiming test obtained from seven subjects show that eye-hand coordination is moderately disturbed by increased or decreased acceleration. The subjects already adjusted to the situation during the first six exposures to weightlessness.

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The authors wish to express their thanks and appreciation to Airmen First Class Raymond D. Rinker and Tommie L. Shinholster, who worked as crew chiefs in maintaining the aircraft and preparing the flights, and to the test subjects in this study who participated in the experiments.

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SELECTION AND TRAINING OF PERSONNEL FOR SPACE FLIGHT

by

D.H. Beyer and S.B. Sells

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Selection and Training of Personnel for Space Flight

MAJOR DAVID H. BEYER, USAF (MC) and SAUL B. SELLS, PH.D.

THE ACCOMPLISHMENT of powered flight into space will depend not only on the development of suitable cabins, propellants and engines, but also on the equally important issues of selection and training of space crews. It is the purpose of this report to formulate, in the light of presently available information and opinion, a tentative outline of crew requirements for spaceships and then to interpret these requirements as a rational basis for guiding needed research on selection and training.

The discussion is premised on an orbital space flight to a circular satellite orbit from 500 to 600 miles above the earth's surface. The period of rotation of a spaceship at this altitude, in equilibrium with the force of gravity, is approximately two hours.[3] The first manned flight very likely will remain in a near circular orbit for weeks or months if no severe technical difficulties are encountered. From present concepts of the size of the cabin and its crew stations, it is estimated that the crew will consist of one to five members. Each will be required to be cross-trained for every crew duty and as a group they must operate in a co-ordinated fashion. Their missions will involve close physical proximity and co-operative activity for prolonged periods. As far as can be anticipated, the engineering of the cabin will provide sufficient protection so that no physiologic or medical qualifications, other than those currently in force for pilots, will be required. However, it is apparent that the mission will involve extremes of potential hazard of both physiologic and physical dangers, and will be capable of arousing intense fears of circumstances and possibilities unknown. At the same time this task is most enticing in prospects for glory and

From the U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas.

Dr. Beyer is now chief of the aviation medicine branch, Office of the Surgeon, Far East Air Forces, APO 953, San Francisco, Calif.

distinction in pioneering a new frontier—today's frontier of interplanetary space.

With these requirements and prospects, the two problems of selection and training will be considered. It is unlikely that the first crew will be "selected" in the conventional sense in which the term aircrew selection is understood. They will be men who have displayed genuine interest and competency for this job through association with the projects of designing, building, and testing prototypes and the actual vehicle in early flights. Nevertheless, these men must be qualified adequately in the attributes which will be required in subsequent selection of space crews.

SELECTION

In analyzing the personnel requirements for any situation it is necessary to consider the following aspects of the problem: (1) the aptitude and skill requirements essential for performance of the task; (2) the biologic and physical requirements related to the environment, the machine and the mission; and (3) the psychologic stresses which may be anticipated and the tolerances they imply.

Aptitude and skill requirements.—Because all crew members must be cross-trained and the pilot will have the pivotal responsibility, this analysis is based on the position of pilot.

Present concepts of the space craft suggest that its operating characteristics will not be radically new. It is expected to be very much like a conventional rocket ship. Once launched into orbital flight, mainly by automatic controls, the ship will have to be monitored to a certain degree during the time it is in orbital flight and then brought down through the atmosphere to a landing. Once within the atmosphere a conventional landing will be made by the use of wings and a tricycle gear, after an extended glide, quite like the landing of a large jet aircraft. Descent and landing will require essentially the same skills as those used in the pilotage of medium and large jet aircraft. Training and experience in piloting jet and rocket aircraft will be most useful for transition to the space craft.

Using trained jet and rocket pilots as a source of personnel, the critical aptitude and skill requirements for space crew members tentatively appear as follows, when considered in relation to the requirements set forth earlier: (1) expert knowledge and proficiency in piloting high-performance aircraft (minimum experience and proficiency requirements could be used effectively to screen in this area); (2) a high level of general intelligence; (3) high mathematical and numerical ability; (4) knowledge and proficiency in aeronautical and electronics' engineering, demonstrated by a formal training prerequisite and/or performance on an examination; and (5) knowledge and proficiency in navigation and astronomy sufficient to learn the fundamentals of astronavigation as well as high speed, high level aeronavigation. These proposals may be regarded as hypotheses subject to empirical validation.

The selection of pioneer crews for initial flights will doubtless follow the same pattern as that which has of

necessity prevailed in selection of outstanding present test pilots—such as Yeager, Bridgeman, Smith, Everest and Murray—who are recognized for their pre-eminent ability and interest in meeting new challenges.

Biological and physical selection requirements.—The general configuration of the orbital space craft is the first concern. Because of the necessity of the return of this craft to the earth and its aerodynamic landing, it will have a configuration generally conforming to present medium and large jet bombers and transports, with certain modifications. For example, von Braun stated in "The Mars Project" that the length of the third stage of the ferry vessel will be 15 meters, its aft diameter 9.8 meters, its wing span 52 meters, and its wing area 368 spare meters.[6]

The cabin of the inhabited space craft will be sealed and the temperature and atmosphere will be automatically controlled. Instruments will be numerous and complex, and every effort will have been made to engineer mechanical and interpretative errors out of them. Working and living facilities will be reasonably habitable and utilitarian. Adequate space will be provided for rest, limited exercise and recreation.[2] Von Braun predicted that an upper limit of 9 *g* would be imposed during take-off and a much lesser deceleration than this on landing.[6] Very recently Preston-Thomas and his associates published similar estimates.[4]

Some tentative biologic and medical selection standards can be proposed for crew members of this type of spaceship. In the first place, persons of ordinary dimensions are indicated and no unusual muscular strength appears necessary. Present day physical standards for jet pilots appear to be appropriate, at least as a minimal qualification. Tests of individual tolerances to special stresses, such as prolonged high *g* force,[1] zero gravity conditions, and prolonged wearing of pressure suits, should be investigated for inclusion in the physical selection procedure. Eventually the entire examination should be validated against appropriate criteria in the same manner as the other selection tests.

Psychiatric and psychologic adaptability requirements.—The final consideration in selection is concerned with the psychologic stresses of the mission on the crew members. It is essential to eliminate candidates who may be considered unlikely to maintain efficient performance while experiencing the actual and perceived hazards, threats and deprivations of space flight. This area of selection is difficult and complex, and the one in which there is perhaps the least complete information today. Nevertheless, it is recognized that further assessment is required of the individuals qualified on the first two sets of standards to determine their fitness to adapt to the peculiar stresses of this type of mission. The personnel to be assessed will be experienced pilots of high performance aircraft and may be assumed to have already accepted the usual stresses and dangers of flight. These factors could probably be best considered by reviewing critically the experience and the history of hazard exposure of the candidates.

Additional stresses over and above those of jet and rocket flight must be considered. In our opinion, by far the greatest problem involves the implications of a seemingly complete break from the earth and the protective societal matrix in a small, isolated, closely confined container with a few companions. Little is known today about the effects of confinement and social isolation on individual and group behavior, particularly under the hazardous and threatening conditions of space flight. We believe that research on these problems may indicate important possibilities of improving the habitability of the space craft and of achieving an optimal group structure for efficient operation under the assumed conditions. Based on current scientific knowledge, we can only speculate on the characteristics of the person most likely to enter such a situation with confidence, equanimity and the least likelihood of psychologic breakdown or interpersonal conflict.

The following proposals might serve as hypotheses for selection research in this area. They are formulated in terms of presumed favorable and unfavorable characteristics in relation to the situational demands.[5]

1. Motivation. The successful applicant is expected to manifest intense motivation for this project. This may be revealed through an enduring interest in this general field, supported by tangible evidence, such as special readings, courses or studies of subjects related to space flight (e.g., astronavigation, rocket fuels and satellite construction), participation in test flight, engineering or other aspects of research or development projects, or other activities expressing interest as manifested in studies, occupational and recreational choices. Although this selection program will be confined to volunteers, the assessment should ascertain that desire to participate is *thus* consistent with an expectation of adequate need satisfactions rather than expressions of neurotic problem solution, such as viewing the project as a substitute for other supports catering to immature dependencies or as a means of therapy for their neurotic strivings.

2. Cooperation. Because it is expected the job will demand co-operation as well as skill, importance is attached to ability to relate well with associates and assume responsibilities in a co-operative situation. This implies the capacity freely to place trust and confidence in associates as well as to win their trust and confidence. Underlying this capacity are positive interpersonal attitudes, mature character integration and emotional stability, involving an inner sense of duty, responsibility, self-control and restraint.[5]

3. Adventurousness. Characteristics indicative of willingness and ability to take calculated risks appear also to be essential. In effect, these describe persons who are characteristically daring but not foolhardy. To a large extent these characteristics may be reflected in the man's flying experience and military history, but systematic methods of assessment need to be devised and validated.

Established psychologic tests or psychiatric techniques are not yet available to assess these characteristics, although research in this school is developing useful instruments and approaches in this general area. The importance of these problems argues strongly for the continuation of long-term research focused on these problems.

TRAINING

Training and preparation of those selected as suitable for the job will

probably require several years prior to takeoff. This phase will involve the last major source of pre-mission attrition because of the high degree of selection which will already have been accomplished. It seems reasonable to expect that the training will involve three phases: (1) ground school or academics, (2) simulator training, and (3) transition flight training within the earth's atmosphere and at space equivalent levels.

The first space crews are expected to be pioneers who, in many respects, will have to be their own instructors. They will have the help and advice of many technical experts and will gradually go beyond the points where many of our present test pilots are now probing. Much of their work in the simulator and transition phases will proceed necessarily on a trial and error basis. However, everything indicates that their task will consist primarily of a gradual extension of contemporary flying techniques to the problems of the new altitudes, speeds and media which they will invade. These men and the procedures they develop, together with the correlated knowledge accumulated through their experience, will constitute the eventual basis on which more formal training programs will be constituted.

Present concepts of space flight suggest that academic training should consist of advanced studies in applied and theoretical mathematics, electronics, engineering, navigation, astronomy and astronavigation. Intensive courses on the design and construction of the spaceship, familiarization with the control of the ship under normal and emergency conditions and, finally, detailed instruction in basic spatial aviation medicine should be included.

The training sequence employing an appropriate simulator developed for this specific purpose will probably be conducted during and following the academic training phase. It is possible to envision this as a synthetic instrument training cabin in which the crew can learn and become familiar with procedures, the characteristics of the instruments, the cabin, and personal equipment as well as working with each other as a co-ordinated team.

Transition will complete the training and may necessarily involve using both a balloon gondola and an actual spaceship either towed or carried to altitude, or powered by more conventional means. In this phase the crew will gain experience in the characteristics and maneuvering of the ship within ranges of altitude where the atmosphere still has aerodynamic functions. Following this may come the final exercises of short, rocket-powered journeys into space equivalent areas and under gravity free conditions.

CONCLUSIONS

The problems of selection and training of space flight crews have been reviewed with tentative proposals based upon present concepts of the characteristics of the early space craft and its probable mission. Because these proposals must be both general and tentative until they are modified by mockups and actual experience supported by research, emphasis was placed on defining problems and presenting the broad outlines of a plan rather than a blueprint. One conclu-

sion which seems of particular interest as a consequence of this analysis is that space flight is not drastically different from most aspects of aviation which are now familiar. When engineers solve the remaining problems of development, it is expected that personnel will be available with the resources and capabilities to undertake the mission. Space flight may thus be approached as the addition of another dimension to the gradual unfolding of the sciences which have already made magnificent accomplishments in powered flight. However, it is necessary that research and interest in the human factors' aspects keep abreast of progress in engineering.

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THE LABYRINTHINE POSTURE REFLEX (RIGHTING REFLEX) IN THE CAT DURING WEIGHTLESSNESS

by

Siegfried J. Gerathewohl

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AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

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The Labyrinthine Posture Reflex (Righting Reflex) in the Cat during Weightlessness

By Siegfried J. Gerathewohl, Ph.D., and
Major Herbert D. Stallings, USAF

ALTHOUGH it is generally accepted that linear acceleration is the physical stimulus for the otolith organ, its function during periods of increased and decreased gravity has not been clarified.[3,8,15] In 1952, Slater[16] discussed the probable response of the otoliths to the weightless condition by drawing some tentative conclusion from morphologic data and electrophysiologic experiments made by Adrian[1] and Lowenstein[9], and by Lowenstein and Roberts.[10] The experiments in this report deal with the otolith functions of the cat. The findings are thought to throw some light on the vestibular processes during subgravity and zero-gravity.

The means of sensing the effect of gravity, which is actually a linear accelerative force, is provided by a set of mechanically affected organs of the inner ear known as otolith organs. They are located in the utricle and the saccule which are filled with endolymph and contain the very specialized structure of macula and otoliths. The otolith apparatus consists of a plaque of hair cells covered with a mucus layer, which carries a large number of very small particles of calcium carbonate, the so-called otoliths. When the head is in an upright position, the macula of the utricle lies approximately in a horizontal plane, that of the saccule in a vertical plane. The planes of the two saccular maculas form an angle opening forward and downward.

The probable response of this organ to weightlessness has been discussed elsewhere.[6,8] Because of their physical characteristics, the otoliths are "gravireceptors." They can move within the macula under the pull of their own weight, or in response to accelerative forces and their inertial effects. This movement bends or pulls, or shears the epithelial hairs, thus distorting the

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From the U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas.

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sensory cells and producing a stimulus. Depending upon the position of the head in the state of rest, the end organs of the utricle and saccule are affected in a certain way. The forces of gravity and acceleration, caused by voluntary and involuntary motion, are also conveyed to the brain in the form of impulses traveling along the vestibular nerve. These impulses are all of the same intensity but they vary in frequency depending upon the direction and mode of acceleration.

The weight or movement of an otolith distorts the cell or cells closest to it. Minimal stimulation occurs when the maculas are horizontal and the otoliths rest on the hair cells; maximal stimulation is obtained when the otoliths hang from the cells or, with normal head position, when they are pushed upward. Now, in the weightless state, the otoliths are deprived of their weight, too, and this should result in a minute change of the cell structure. This then will bring forth an alteration of the impulse rate of the vestibular nerve.

It is the opinion of many investigators that the force of gravity exerts the most fundamental influence upon our spatial orientation.[2,7,11,14] However, there is no need for the organism to obtain a conscious knowledge of the direction and amount of gravity. The basic need is for a mechanism that adapts the body automatically to their effects. This is done by means of the so-called postural reflexes which are thought to serve to maintain or restore the "normal" position and posture of the body. This group of reflexes, which includes the static and statokinetic reflexes of the body, reveals that gravity has an essential effect upon animal life. This effect is very difficult to assess but relatively easy to demonstrate.

One of the best-known reflexes of this sort is the postural righting reflex of the cat. Since the pioneer work of Magnus,[12,13] this reflex has been studied under various conditions. If a cat is first held in any other than normal position and then dropped, the animal immediately turns into the normal posture so that it always lands on its feet. A similar reaction occurs when the cat, lying on its back with its head held in an almost normal position, is moved vertically downward. However, this reflex does not seem to function when the cat is moved upward. Adrian's experiment on the cat has shown that changes in head position were associated with an alteration of the impulse rate, which was caused either by the act of tilting or by the angle of tilt as such. He found that pressure toward the macula did not increase the stimulus. This may account for the lack of postural righting reflex during movement in the upward direction.

From a practical viewpoint the question was asked how the righting reflex of the cat would work during subgravity and zero-gravity. Would the cat turn around when held upside down or would it stay in this position? Is there a time factor involved which may indicate adjustment and adaptation? How will other cues—for instance, visual orientation—affect the functioning of the reflex? The answers to these questions were sought not only to satisfy our own curiosity,

but to clarify the role of the otolith organ during weightlessness.

METHOD

Eight cats were used in the experiment; all were healthy young animals born in the School of Aviation Medicine cat and dog kennels, and raised from three different litters. Four of the kittens were about three weeks old when used in the experiment; two of the kittens were about eight weeks, and two young cats were about twelve weeks of age. The experiments were conducted as follows:

Each of the three sets of experimental animals first was taken into the School of Aviation Medicine film studio and placed on a table. The animals were then lifted up individually and held upside-down in a long stretched position. They were released unexpectedly and dropped from an altitude of about 20 inches. When the three-week-old kittens were employed, the table was covered with a rubber pad. In some of these experiments the animals were blindfolded to exclude visual orientation. The behavior of the animals was recorded on film. This experiment was repeated several times so that its result could be considered conclusive.

The animals were then taken into the air and exposed to short periods of weightlessness. Virtual weightlessness, or a state of reduced gravity, was produced by flying a jet type aircraft (T-33 or F-94) along a Keplerian trajectory.[4,5] The ascent to 20,000 feet was made at a rate of climb of 2,000 feet per minute. The cabin pressure at that altitude was about 9.5 psi, which is equivalent of an altitude of approximately 12,000 feet. The pilot of the craft (H.D.S.) flew the ascending arc of the parabola at full throttle and the descending part with about 75 per cent rpm in order to obtain weightlessness for about 25 to 35 seconds. Absolute weightlessness or zero-gravity occurred for only a few seconds during each of these maneuvers due to the small accelerative forces present. These unavoidable accelerations were of an estimated magnitude of about 0.03 to 0.05 G. The weightless state was indicated and controlled by the conventional G-meter installed in all fighter type aircraft. Before entering into the parabola and during recovery from the dive, accelerations of 1.25 G were not to be exceeded because it was observed during the first flight that the cats were extremely sensitive to an increase of acceleration. Five or six parabolas were performed during each experimental flight.

The small kittens were taken along in pairs and kept in a container until the working altitude was reached. The older animals were used one at a time and carried on the arm of the experimenter in the aircraft (Fig. 1). The cats were turned upside-down and released after periods of 1, 5, 10, 15, 20 and 25 seconds after entering the weightless state. The behavior of the animals was studied under both blindfold and nonblindfold conditions and recorded on film.

Motion pictures were made using a 16 mm. Filmo camera, model 70 H, with a 13 mm. lens, f = 1.5, and a film speed of 24 frames per second. Kodachrome film with a Kodak No. 83 filter, and one Eastman Panchro-

Fig. 1. Photograph of cat before the experiment in the T-33 aircraft.

Fig. 2. Prompt righting reflex of cat immediately upon entering the weightless condition.

Fig. 3. Delayed reflex: the cat turns slowly after a certain delay.

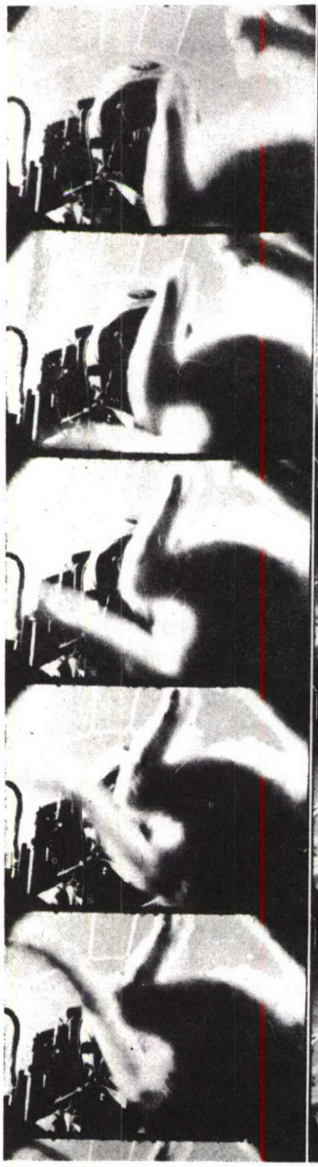

Fig. 4. Postural righting reflex fails completely; the cat floats in an inverted position.

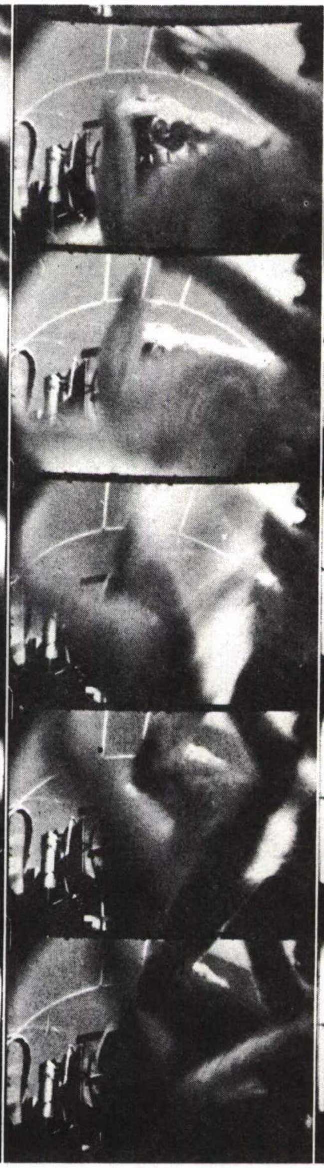

Fig. 5. Disturbed reflex associated with slight tumbling.

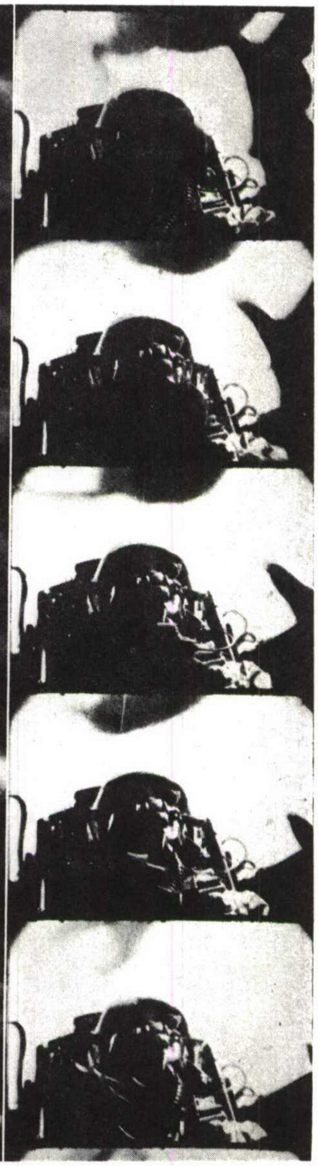

Fig. 6. No righting reflex. The animal floats slowly upwards due to acceleration in this direction (so-called "negative G").

matic black-and-white film for illustration purposes, was used. The camera was attached to the airframe on top of the instrument panel between front and rear seat of the T-33 aircraft, and focused at a distance of about 100 cm. In the F-94 aircraft the camera was installed below the rear panel and focused slightly upward at a distance of about 75 cm. It was switched on shortly before each parabola and stopped at the end of it. Some illustrations of the results are given in Figures 2, 3, 4, 5 and 6. Unfortunately, the animal is only partly visible in these pictures because of the small field size and the limited elevation of the camera.

The evaluation of the films consisted of an analysis of the moving pictures as well as the stills by describing briefly the behavior of the animals with regard to promptness or delay of the righting reflex under the conditions of reduced gravity. To this end, the films were run at normal speed and additional checks of each scene of exposure of the cat were made by looking at each individual frame when the film was moved by hand. The observations were then tabulated; the reflex response was related to the length of time spent in the weightless condition. Thus, some numerical results were obtained which must be considered for what they are worth.

RESULTS

Even before the experiments were started it was observed that the four younger animals fell straight down when they were dropped on the ground. We found that the postural righting reflex of the cat develops during the fourth till sixth week after birth. Hence, in describing the behavior of our animals we must distinguish between (1) the three-week-old kittens whose postural righting reflex was not developed, and (2) the eight and twelve-week-old ones whose reflex was well established. We can summarize the behavior of the first group very briefly.

The motion pictures of the younger kittens made on the ground and in the air show very clearly that in not a single case did the animals turn around after they were released. They fell or floated in an inverted position under normal gravitational and under subgravitational conditions, respectively. Since the righting reflex was not developed, blindfolding was meaningless, of course. The responses of this group of animals were not tabulated due to the uniformity of behavior.

The behavior of the older animals, on the other hand, showed considerable differences under the various experimental conditions. On the ground, the reflex functioned promptly and so unanimously that the results were not tabulated either. The responses of the four older animals upon exposure to weightlessness, however, were tabulated and are given in Tables I and II. In the first table, the behavior of the two eight-week-old kittens is described. As can be seen in this table, the animals turned back into their normal posture at the first exposure to weightlessness. This reflex seems to be delayed or disturbed in the later trials. Table II contains the description of the two oldest animals. Again, the general impression is that the cats turn

TABLE I. BEHAVIOR OF THE ANIMAL WHEN EXPOSED IN AN UPSIDE-DOWN POSITION TO SHORT PERIODS OF WEIGHTLESSNESS AT VARIOUS INTERVALS AFTER THE SUBGRAVITY STATE BEGINS

Animal	Parabola	No. of Exposure	Condition	Time	Response
Grey kitten A	1	1	Eyes open	Immed.	Prompt righting reflex
		2	Eyes open	5	Delayed righting reflex
		3	Eyes open	10	No righting but tumbling due to wild motor response
	2	1	Eyes open Normal position	Immed.	Floating upward and delayed turning upside-down due to accelerations acting in the opposite direction (negative g's).
	3	1	Eyes open	10	No righting
		2	Eyes open	15	No righting and floating upside-down for a few seconds
		3	Eyes open	20	No righting reflex
		4	Eyes open	25	No righting reflex
	4	1	Hood	10	No righting reflex
		2	Hood	15	No righting reflex
		3	Eyes open	20	No righting but tumbling
		4	Eyes open	25	No righting but floating
		5 (?)	Eyes open	30 (?)	No righting, floating upward
	5	1	Hood	5	No righting, floating upward
		2	Hood	10	Righting, tumbling
		3	Hood	15	No righting; floating upward and tumbling
Grey kitten B	1	1	Eyes open	Immed.	Righting reflex somewhat delayed
		2	Eyes open	5	No righting, floating upward
	2	1	Hood	Immed.	Righting, floating upward, turning again upside-down
		2	Hood	10	No righting, floats upward and downward upside-down
	3	1	Eyes open	5	Righting and turning about longitudinal axis
		2	Eyes open	10	Delayed righting
		3	Eyes open	15	Righting reflex
	4	1	Hood	Immed.	Righting
		2	Hood	5	No righting but tumbling into vertical, then normal
		3	Hood	10	Delayed reflex
		4	Eyes open	20	Floats downward, then delayed reflex
	5	1	Hood	5	Floats upward, tumbling
		2	Hood	10	Floats upward, tumbling and turning in normal position
	6	1	Eyes open	10	Righting
		2	Eyes open	15	Delayed righting and tumbling

into the normal position during the first exposures; but that the reflex is delayed or does not occur at all toward the end of the experiments.

To obtain a clearer picture of the occurrence and mode of the righting reflex, particularly in regard to the time factor, the responses of the four older animals were tabulated (Table III). In this table, the beginning of the exposure of the cat to be weightless condition is indicated by time values from one to twenty-five seconds, which are approximations because of the awkward situations which sometimes occurred when the animal refused to be released or clung to a foothold in the cockpit. In column 2, the given number of parabolas varies from five to six for the respective animal. Column 3 is subdivided in responses obtained under blindfold and nonblindfold conditions; the first number being smaller because the animal succeeded in stripping off the hood on several occasions.

An inspection of Table III confirms the observations made in the aircraft and the general impression obtained from Tables I and II. Upon release immediately, or not later than about 5 seconds, the animal turned into the

TABLE II. BEHAVIOR OF THE ANIMAL WHEN EXPOSED TO SHORT PERIODS OF WEIGHTLESSNESS IN AN UPSIDE-DOWN POSITION AT VARIOUS INTERVALS AFTER THE SUBGRAVITY STATE BEGINS

Animal	Parabola	No. of Exposure	Condition	Time	Response
Black and white cat	1	1	Hood	5	Prompt righting reflex
		2	Hood	10	Prompt righting reflex
	2	1	Hood	5	Prompt righting reflex
		2	Hood	10	Normal position, turning upside-down due to acceleration in opposite direction (negative g's)
		3	Hood	20	Delayed righting reflex and turning
	3	1	Eyes open	10	No turning, floating upward, grasps top string
	4	1	Hood	Immed.	Righting reflex
		2	Hood	5	Righting reflex
	5	1	Hood	Immed.	Righting reflex
		2	Hood	5	Righting reflex
		3	Hood	10	Floating, no reflex
		4	Hood	15	No righting reflex
		5	Hood	20	No righting reflex
	6	1	Hood	Immed.	Righting reflex
		2	Hood	5	Floating upward, no turning, grasps top string
White cat	1	1	Eyes open	5	Floating upward, delayed righting reflex
	2	1	Eyes open	5	Prompt righting reflex
		2	Eyes open	10	Prompt righting reflex
		3	Eyes open	15	Prompt righting reflex
	3	1	Eyes open	5	Righting reflex
		2	Eyes open	10	Floating upward, no righting
		3	Eyes open	15	Floating upward, tumbling but no righting reflex
	4	1	Eyes open	5	Floating upward, no righting reflex
		2	Eyes open	10	Floating upward, no righting reflex
		3	Eyes open	15	Floating briefly, no righting reflex
	5	1	Eyes open	Immed.	Righting reflex
		2	Eyes open	5	Delayed righting reflex
		3	Eyes open	15	Righting reflex, slightly delayed

normal position eleven times when visual cues were available, and ten times when they were blindfolded. After a latency of about 15 or 20 seconds, the righting reflex occurred or failed about the same number of times when the cats were not blindfolded. When the hood was used, the same ratio of responses was already obtained after 10 seconds. From this time on the reflex failed in five cases. With eyes open no righting response was observed among the few cases exposed after a period of twenty-five seconds. By and large, we found that the postural righting reflex ceased to function after a stay of more than twenty seconds in the weightless state; and that visual cues did not seem to affect the reflex to a marked degree.

DISCUSSION

Magnus[12] has demonstrated that normal animals acquire and maintain posture by various static and statokinetic reactions. In our experiments, both types of reflexes will also be activated because the cat normally does not like to lie on its back, nor to be moved in this position in a vertical direction. When a cat is held back downward and then allowed to fall, the otolith reflex acting upon the neck muscles turns the head of the animal rapidly into its normal position. The contraction of the neck muscles, which rotate the head, activates the myotatic neck reflexes which affect the muscles of the body by turning the thorax and then the pelvis into the normal posture. This reaction can be seen in pictures

TABLE III. OCCURRENCE OF RIGHTING REFLEX AT VARIOUS INTERVALS AFTER THE SUB- AND ZERO-GRAVITY STATES BEGIN

Animal	Parabola	Beginning of Exposure of Animal in Seconds											
		With Eyes Open						With Hood					
		1	5	10	15	20	25	1	5	10	15	20	25
Grey kitten A	1	+	±	−									
	2	x*											
	3			−	−	−	−						
	4					−	−			−	−	−	
	5								−	+	−		
Grey kitten B	1	+	−										
	2							+		−			
	3	+	+	+									
	4				+	+		+	−				
	5								−	±			
	6			+	±								
Black and white cat	1							+	+				
	2							+	x*	±			
	3			−									
	4							+	+				
	5							+	+	−	−	−	
	6							+	−				
White cat	1	±											
	2	+	+	+									
	3	+	−	−									
	4		−	−	−								
	5	+	±	±									
Righting reflex (+)		6	2	3	1	1		7	3	1			
Delayed reflex (±)		1	2	1	1					2			
No righting reflex (−)			3	5	2	2	2		4	3	3	2	

*Animal was held in normal position and an acceleration opposite to the direction and stronger than the force of gravity was employed.

of a promptly functioning righting reflex (Fig. 2).

Although we have enough evidence to assume that the postural righting reflex was generally produced by an otolith response, this reflex can be reinforced by exteroceptic or visceral stimulation. Because the animal was symmetrically supported in our experiments, reinforcement of the postural righting reflex by the so-called "body righting reflex" can be neglected. However, there is the possibility of a certain reinforcement through the loss of touch and grip pressure during the release of the animal. This may account for some of the reflex actions in an advanced state of weightlessness.

Because visual cues play a prominent role for the orientation of the cat, the occurrence of the so-called "optical righting reflex" was controlled by means of the hood. This reflex was observed in those cases in which the animal turned or stretched itself in order to grasp the top or the side of the canopy. There is some evidence from Table III that blindfolding changed the reflex pattern but slightly.

Naturally, we cannot expect the righting reflex to occur before it has been developed. After this was accomplished, the reflex should fail only if there is a complete lack of stimulation. During the transition from the normal state of gravity into subgravity, the gravireceptors are stimulated.

This may have caused the righting response of the animal when released immediately upon entering the weightless state. On the other hand, if the animal was in this state for a certain period of time and was then released, the reflex was delayed or failed. It should have failed completely if true weightlessness were obtained. Hence, it seems that the righting reactions observed toward the end of the parabola were caused by the slight changes in acceleration, which unfortunately occurred during most of our weightless periods.

The response pattern obtained in our experiments must be attributed to the changed stimulus pattern of discrepant gravitational, visual and tactile cues which caused spatial disorientation. This may be the main reason why the animal became so confused and fought against being exposed to the weightless condition, and why the postural reflex was disturbed. These experiments also show that the otoliths most probably are not stimulated by acceleration as such, but by the changes of acceleration. In the weightless condition of our experiment the animal is subjected to the constant acceleration of gravity, but this ~~force~~ does not seem to activate the postural righting reflex. Physiologically, this is understandable because it is the initial change of the physical state of the otoliths that produces an inertial effect to elicit the sensory stimulus indicating the alteration of the physical condition. Thereafter, the otoliths "move along" with the maculae, and only the alteration of this condition by deceleration brings forth the inertial effects that will stimulate the gravireceptors again.

How powerful this stimulation can be was demonstrated by the two exposures of the cats to accelerations producing centrifugal forces different from the direction and stronger than the force of gravity. The black and white cat tended to turn in the apparent direction of gravity, but the reflex was delayed and incomplete due to the almost normal position of the head. The grey kitten turned immediately from the normal position upward and landed in an inverted position at the top of the canopy. In this case, the physiologic condition was very similar to that when the kitten was dropped in the upside-down position. Because the posture of the head was inverted from one condition to the other, the inertial effect on the otoliths is the same when the direction of acceleration is reversed. The inverted righting response occurred although visual cues were available.

SUMMARY AND CONCLUSIONS

Experiments on the postural righting reflex were made using (1) four young kittens before the reflex was developed, and (2) four older kittens with the reflex well established. On the ground, the animals were dropped in upside-down position from an altitude of about twenty inches, and later in the air exposed to periods of about twenty to thirty seconds of practical weightlessness. The reflex was studied in T-33 and F-94 aircraft under both blindfold and non-blindfold conditions. The behavior of the cats was recorded on 16 mm. film.

The motion pictures were evaluated by repeatedly watching the film, and by an analysis of the individual frames. On the ground, the younger animals fell straight down; the older ones turned upright immediately after release without exception. In the air, the younger kittens floated upside-down during weightlessness; the older ones turned upright at the beginning of the weightless state, but their reflex failed after several exposures. By and large, it was observed that the postural righting reflex of the cat ceased to function after a period of about twenty seconds of practical weightlessness; and that the available visual cues did not affect essentially the reflex pattern.

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PLANTS AS A MEANS OF BALANCING A CLOSED ECOLOGICAL SYSTEM

by

James G. Gaume

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SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Plants as a Means of Balancing a Closed Ecological System*

James G. Gaume†

Randolph Air Force Base, Texas

Abstracts

This paper presents a discussion of the theoretical possibilities of the use of green algae in effecting a symbiotic relationship between man and plant in closed systems, such as a manned satellite or spaceship cabin.

The earth, with regard to all forms of life, is a wonderfully balanced ecological system. Contained on it and in its atmosphere are all the elements necessary to sustain life in the various forms present in the system. We are not fully aware as yet of the part which each known element plays in maintaining the balance between plant and animal life. We do know, for instance, that the waste products of animal metabolism contain elements which are necessary for flourishing growth of plant life, and vice versa.

When the normal balance of the Earth's system becomes upset, either through some natural phenomenon or as a result of some activity of man, inadvertent or considered, nature has a way of restoring the balance by means of some very unusual occurrence. Thus, the eruption of a volcano replenishes the carbon dioxide in the air, and in addition showers the surrounding land and water with lava and volcanic ash which contain the common and trace minerals which we know now to be necessary for good plant growth.

We know, too, that the relationship between plants and animals is not entirely symbiotic, but that in many instances it is dog eat dog—small animals are devoured by larger ones, which in turn are consumed by still larger animals. The same is true of the fish in the sea. On both land and sea are plants which devour insects, fish and small animals[15], which are caught in their clutches.

The basic source of food for the animal is the green plant. The plant takes light from the sun, carbon dioxide from the air, nitrogen, water and other elements in various forms from the soil, and synthesizes them into carbohydrates, proteins, and fats. The plant then serves as food for the animal organism, which ingests the plant in its natural form, breaks it all down and puts the parts back together again in a form which is acceptable to that organism. What is left after the animal metabolic processes have been completed, is returned to the soil, in the form of organic semi-solid waste, or to the air as gaseous carbon dioxide. Water, of course, in various amounts, accompanies all forms of waste excretion. Food comes to humans directly as plant products, or indirectly, first having been changed into an animal food source.

The return of animal waste to the soil, and the decomposition of dead plant structures, replenishes the necessary growth factors removed from the soil by growing plants. The Chinese rice farmer has known this for several millennia and utilizes all excreta as fertilizer for his rice crop. His method of doing so, however, is objectionable to us, esthetically, and is fraught with the dangers of transmitting disease. We, therefore, have developed methods of changing waste matter into the acceptable form of commercial fertilizer. The same is being done with food waste, by means of digestive bacterial action, to produce another form of fertilizing compound.

The point is, that all forms of natural waste can be utilized to enrich the soil and promote growth of essential plant foods, thus completing the cycle in the transformation of energy as it is used to sustain and make flourish the growth of living organisms.

Man, animals and plants require oxygen for cellular respiration of food substances. As a part of their metabolic processes, plants require and take up carbon dioxide from the air. During the photosynthetic phase of metabolism plants produce oxygen in excess of their needs. In the dark phase, exogenous oxygen must be available. Under proper conditions, however, a net oxygen gain can be accomplished over a cycle of light and dark phases. Man and animal can respire the oxygen, producing carbon dioxide which is utilized by plants. Thus we are furnished with another example of the mutually beneficial existence which occurs between animal and plant.

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† Department of Space Medicine, USAF School of Aviation Medicine. Present address: Chief of Space Medicine, The Martin Company, Denver, Colo.

So much for the general consideration of the earth as a balanced ecological system. Let us proceed to the main point of the discussion—the use of plants as a means of balancing a small closed ecological system. In establishing this balance, three objectives must be accomplished:

1. to provide a means of gas exchange between human and plant
2. to provide a source of food by harvesting the excess plant growth
3. to provide a means of disposal of the liquid and solid waste from the human.

Conceivably, a miniature sealed system, comparable to the earth, could be set up, which could maintain human occupants in good health—provided a suitable plant organism, or organisms, could be found capable of fulfilling these three objectives.

It is now apparent that such an organism is one which, until recently, has been considered a useless and undesirable one—one of the lowliest of plants—the simple green alga.

Let us consider now the use of algae, as a means of attaining the three goals outlined, and discuss the characteristics which would enable us to use such micro-organisms in a closed system.

1. Gas Exchange—Green algae, such as Chlorella, are particularly suitable as a photosynthetic gas exchanger. They are single-celled, small, round bodies about the size of a red blood cell. Since they have no specialized organs, as do higher plants, the photosynthetic process can be fully utilized in oxygen evolution and in growth, manifested by production of new cells. This activity can continue endlessly, in algae, without the presence of a dark phase, if light and nutrients are plentiful.

The potential oxygen production of such algae is extremely good. Studies in this area are now being made by Dr. Jack Myers, at the University of Texas, under an Air Force contract with the School of Aviation Medicine. Dr. Myers has found that five pounds, fresh weight, of the common alga Chlorella pyrenoidosa under optimal conditions, is sufficient to support one man with regard to gas exchange.[9] This means that five pounds of the algae can produce enough oxygen to meet the needs of one man, and can absorb the carbon dioxide produced by one man, during a given period of time. Thus, one human and five pounds of this alga, under suitable conditions could live symbiotically in a sealed cabin with regard to oxygen and carbon dioxide exchange.

Chlorella pyrenoidosa, in short-term experiments, attains maximum growth rate at low light intensities, whereas maximum oxygen evolution occurs at considerably higher illumination, in experiments of the same length.[16] In long-term experiments, the growth rate and oxygen production curves become almost the same. This is excellent for our purpose, as we shall see later.

In continuous growth experiments of longer duration, the optimum light intensity for these two factors is 500 foot candles of light. By comparison, the incident sunlight available at the earth's surface is 10,000 f.c. of light, or slightly more. Thus, relatively low light intensities are required for algae growth and oxygen evolution over long periods of time.

Recent work by Kok[5] and Myers[13], has shown that an intermittent illumination might produce better results than a continuous source of light. In this instance, higher intensities are more efficient. The algae are illuminated for 2 milliseconds, and are in the dark for 20 milliseconds at about 5,000 f.c. of light.

Chlorella and Scenedesmus have been used most for experimentation because of their ready availability, but other algae may be more proficient in producing oxygen. Myers has found that a given mass of Anacystis nidulans, a blue-green alga found in Texas ponds, has a potential oxygen evolution three times greater than an equal mass of Chlorella pyrenoidosa, but in order to obtain this amount of oxygen, Anacystis can absorb, and must be illuminated with three times as much light as Chlorella.[11] With this alga, then, there is in the possibility of obtaining a surplus of oxygen, using the same mass of algae, as in the case of Chlorella, or of being able to use only one-third the mass of algae to produce the same quantity of oxygen. In the sealed cabin of a space ship this could be a very important factor because of the space required in the craft for the algal equipment.

Little is known, at this time, regarding the potentialities of Anacystis in other directions. Should these possibilities be limited, perhaps a mixture of Anacystis and Chlorella could be used advantageously.

The removal of carbon dioxide is just as important as the rate of oxygen production with algae. Since five pounds of Chlorella can absorb the carbon dioxide produced by one man, this problem would seem to be solved. In the laboratory Chlorella are aerated with five percent carbon dioxide in air, and apparently can absorb all the carbon dioxide, although the algae can get along on much less. The carbon dioxide in expired air is four percent. In our 100 cu. ft. Space Cabin Simulator at the School of Aviation Medicine, if carbon dioxide is allowed to accumulate from one human without its removal, it will reach about five percent in approximately three hours. Navy research has shown that in order to retain normal mental activity that the carbon dioxide level must be not more than 1.5 percent,[19] preferably lower. With absorption by chemicals, we are able to keep the carbon dioxide level at .5 percent in our Simulator. Carbon dioxide buildup and toxicity becomes a problem, in about one-half the time as does the dwindling oxygen supply, if the latter is not replenished in a sealed cabin.[16]

Can an algal system keep the carbon dioxide concentration at the proper level in a sealed system? Studies designed to answer this question are now in progress by Dr. Myers for the School of Aviation Medicine.

2. *Food Production*—The potentialities of algae with regard to production of food are quite good, when one considers the chemical composition of Chlorella[17, 18] and Scenedesmus.[21] The average composition of these algae is 50 percent protein, 15 percent carbohydrate, 25 percent lipids, and about 10 percent ash. This makeup varies, of course, with the composition of the nutrient solution. These algae are strongly oriented to protein synthesis and when grown rapidly in thin suspensions the protein may increase to 70 percent or more. Protein content can also be increased by the use of blue light in illumination.[14] When blue light is used, a larger portion of the carbon dioxide and hydrogen is utilized in the formation of protein. High protein synthesis is also caused by high nitrogen content in the nutrient solution.

Chlorella is very efficient in retaining photosynthetic products within the cell, regardless of the amount of illumination. The net result is the formation of new cells and rapid growth. Some algae are capable of doubling their weight twelve times in one day, under optimal conditions. The amount of organic matter thrown off by Chlorella is extremely small, and the same is true of the number of dead cells found in a growing suspension.

Because such a high percent of algal cells is digestible, as has been mentioned already, and the loss in preparing them as food would be almost zero, algae would seem to be an ideal source of food aboard a satellite or space ship, for flights of the order of weeks or months.

Chlorella contains nearly all the amino acids essential for good health with the exception of those containing sulfur. They are grossly deficient in cysteine and moderately deficient with regard to methionine. Histidine content is, likewise, moderately low. Algae contain also, appreciable amounts

of carotene, or pro-vitamin A, and of the B complex vitamins and Vitamin C. Vitamin D is not present to any great extent.

Thus, it is apparent that algae can be a very adequate source of protein for man, with the addition of cysteine, methionine, and histidine, and can be at least a partial source of the vitamin requirements.

According to Gaffron,[3] if fifty percent of algae is digestible, two kilograms per day is more than enough to keep a man in good health with mineral and vitamin supplements. If used only as a source of protein in the diet, this amount would be enough for five or six people. Geohegan[4] fed rats which thrived on a mixed diet using algae as a sole source of protein. Jorgenson,[3] in the leper colony at Cabo Blanco, Venezuela, fed algal soups to patients suffering severely from malnutrition and the state of their nutrition was greatly improved.

In theory, then, Myers figure of five pounds (or 2.3 Kg) of chlorella, required to balance the respiratory cycle of a man, would be more than sufficient to supply food for the man for a period of one day, repeatedly, provided the alga doubled its weight in 24 hours. This seems quite reasonable in view of the rates of growth which were given earlier.

This food source also would seem to lend itself to the production of concentrated food tablets, by dehydrating, sterilizing and compressing the algae into bite-sized tablets. Such treatment would enable the crew to store economically, with regard to the space required, a large excess of algal food, in the event of an emergency of this nature.

What nutrients are required in the feeding of algae? For the highest protein formation the elements required are nitrogen, carbon, phosphorous and potassium. If the medium is deficient in any one of these, protein synthesis is reduced.[21]

Other elements which must be replaced in a nutrient medium are calcium, iron, magnesium and sulfur, and the micro-nutrients manganese, cobalt, copper and zinc.[6, 21] Recent evidence shows that molybdenum may also be very important, as a trace element.[1]

In other words, the same nutrient materials are required for algal growth, as is necessary for higher plant growth. Since this is so, the elements necessary for algal nutrition can be obtained from the most readily available source, namely, human waste.

In a closed ecological system such as a satellite or space ship cabin, human excreta must be disposed of. What better way to do it than to convert it into a reuseable substance, because wherever possible, all matter will have to be converted from one form of potential energy to another, recycling it over and over.

3. *Disposal of Human Waste*—As if in conformance with the pattern of nature as observed earlier, human waste contains almost exactly the elements required to promote vigorous growth of algae. Nitrogen is abundant in the urine as urea, and comprises approximately 50 percent of the urinary solids. Part of the remaining solids also contain nitrogen. Carbon would be supplied partly from the organic waste of the gastro-intestinal tract, and in part from the carbon dioxide in exhaled air. Phosphorous, potassium, calcium, sodium, sulfur and magnesium are present in sufficient quantities in the urine, to supply the needs of the algae. Some of these are found in semi-solid waste too, including the trace elements required.

From thsee data, it would appear that the three forms of waste from the human body contain all, or nearly all, the essential elements necessary for growth, respiration, and photosynthesis in algae, and in adequate amounts. For this reason, as stated by Gotaas and Oswald[12] at the University of California, it may be considered that sewage is not truly a waste, but contains the low energy forms of every element critical to life. For example, a certain amount of nitrogen is taken into the body and excreted in almost exactly the same amount. If a daily nitrogen balance were made on a normal human, it would be difficult to show any utilization of nitrogen. Only the form and energy level of nitrogenous compounds would be changed. The same is true of the other elements.

Gotaas and Oswald, among many others working in the field of sanitary engineering, have shown that Chlorella will thrive on domestic sewage in open oxidation ponds, and that aerobic bacteria present in these ponds have no detrimental effect upon the growth of the algae. In fact, they aid algal growth by providing carbon dioxide while the algae provide oxygen for the bacteria. These facts may have a very significant effect on certain aspects of our agricultural economy, in years to come. In the pilot plant in California the average annual yield of algae was thirty tons per acre, dry weight, as compared to 1.5 tons per acre annual yield, for the California field crops.[12] Algae feeds have been found to be excellent for livestock. They may eventually replace many of our present livestock feeds.

There is no reason why algae, when prepared adequately for the table, cannot be just as acceptable—yes, even as tasty—as spinach, broccoli, and other green vegetables. In fact, four years ago, algal research scientistis prepared and ate a banquet in which all the courses of the meal were composed partially of algae. The event was a notable success.

Summary

We have seen that, in a closed ecological system such as a spaceship cabin, the possibilities of using algae to attain the three objectives already outlined, are theoretically quite favorable. Although much more data are needed before an algal exchange system becomes a reality, the engineering of such a system, to make it fit in a satellite or space ship, and capable of operating under the environmental conditions which will prevail there, will be as great a challenge as the algal research itself.

The engineering of an algal exchange system must include the following

1. The means of illumination of the algae using artificial or solar light, or both, with a controlled spectrum most suitable for the algal reaction desired.
2. A method of aeration. Cabin air can be bubbled through the algal suspension. Carbon dioxide and the odor gases will be removed from the cabin atmosphere, by the algae, at the same time.
3. Population density measuring devices—probably photometric—in two or more locations in the system.
4. A means of circulation and causing turbulence of the suspension.
5. Nutrient analysis and nutrient addition devices.
6. A harvesting mechanism, probably employing centrifugation or filtration methods.

In addition there must be a suitable means of preparing the harvested algae as food. Lastly, the human waste will have to be processed suitably in a miniature processing plant, in order to be used as nutrients for the algae, since, in this case it would not be desirable to use unprocessed waste.

It must be remembered that this entire system must be able to operate efficiently in a barometric pressure of approximately one-half an atmosphere, or about an 18,000 foot equivalent, *and* in the zero-gravity state. In a zero-gravity environment the engineering problems involved will be greatly increased.

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THE POSSIBILITIES OF AN INHABITABLE EXTRATERRESTRIAL ENVIRONMENT REACHABLE FROM THE EARTH

by

Hubertus Strughold

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

The Possibilities of an Inhabitable Extraterrestrial Environment Reachable from the Earth

BY HUBERTUS STRUGHOLD, M.D., PH.D.

The problem of life on other worlds is a subject which captivates the imagination of mankind tremendously. Not until it was recognized by Copernicus in 1543 that the earth is not the center of the universe but rather only one of the members of the planetary family of the solar system, could such thoughts arise in the human mind. There are two technical events that have had a catalytic effect upon man's occupation with this question: the invention of the telescope some 350 years ago, which has brought the celestial bodies closer to us optically, and recently, the successful development of the rocket which possesses the potentialities of bringing us closer to them physically. Not only has the older question of the existence of indigenous life on other planets come anew into the focus of scientific and general public interest, but in addition, with the development of space operations, this question is posed: Are there planets in the solar system that offer an environment of such kind that an astronaut from the earth—the species homo sapiens terrestris—could land there and stay there for some time at least?

We get an answer to both of these points very quickly by projecting the specifications of the environment required, from the standpoint of human physiology and of general terrestrial biology, against the physical planetary data offered in the astronomical literature.

Such a study can be called planetary ecology. For the science which particularly studies the possibility of indigenous life on the planets the terms "astrobiology" and "astrobotany" are in use. With regard to this latter problem this discussion will consider only the kind of life known to us, based on carbon as the structure atom and on oxygen as the energy liberation atom.

Table I shows a list of certain ecological factors indispensable for the existence of life such as: the presence of an atmosphere and a hydrosphere, or *water* in its liquid state, a biologically suitable temperature, carbon dioxide which is, in addition to water, the raw material for photosynthesis in green vegetation, and finally, oxygen, the key element in the biological energy liberation. The table further shows, by use of the marks + and — whether or not these ecological factors are found on the planets of our solar system. By screening the planets in this way, only Mars and Venus remain as bioplanets or conceivable bioplanets. And these planets are found in neighboring orbits near the sun only. The decisive factor responsible for this zonation of the planets with life-favoring conditions is the intensity of solar radiation

Dr. Strughold is research adviser to the commandant, U. S. Air Force School of Aviation Medicine, Randolph Air Force Base, Texas.

which decreases with the inverse square of the distance from the sun. The difference in the radiation intensities to which the planets are exposed, and have been exposed since their protoplanetary stage, are therefore tremendous.

TABLE I. THE PLANETS AND SOME OF THE ECOLOGICAL NECESSITIES FOR LIFE

Planets	Atmosphere	Hydrosphere	Bio-Temperature	Carbon Dioxide	Oxygen
Mercury	−	−	−	−	−
Venus	+	(+)	+	+	(+)
Earth	+	+	+	+	+
Mars	+	(+)	+	+	(+)
Jupiter	+	(−)	−	−	−
Saturn	+	(−)	−	−	−
Uranus	+	(−)	−	−	−
Neptune	+	(−)	−	−	−
Pluto	+	(−)	−	−	−

+ present, (+) probably present in small amounts.
− not present, (−) present in frozen state.

We get a dramatic picture of this by considering the size of the sun as seen at the distances of the various planetary orbits (Fig. 1). To an observer on Mercury the diameter of the solar disk would appear more than twice the size it does to us on earth. As seen from Mars, the sun would have a considerably smaller apparent dimension than our moon. At the distance of Jupiter the sun's diameter is only one-fifth as large as seen from the earth, and at the distance of Pluto the sun would appear no larger than the evening star Venus appears to us on earth. This means that in the more remote portions of our planetary system, the role of the sun, as dominating source of light and heat energy, fades into that of a common star. If there were people on Pluto, these Plutonians would not even know the concept of a sun. This consideration makes it quite clear why life-supporting planets are conceivable only in a certain zone within the planetary system.

More in detail, the visible section of the solar radiation spectrum presents a narrow zone of physiologically desirable planetary illumination, a kind of "euphotic belt" surrounded by dysphotic (hyperphotic and hypophotic) regions. With this we have added a new ecological factor not mentioned in Table I, namely, light. The infrared portion of solar radiation, as the main carrier of heat energy, is apparently effective in providing biologically acceptable temperatures on planets only in the range from Venus to Mars, which justifies our speaking of a "biotemperature belt" in the planetary system. The occurrence of water in this same zone represents a kind of "liquid water belt" in the planetary system.[5]

Finally a zonal distribution is evidenced in the chemical composition of the planetary atmospheres. On the inner planets we find atmospheres containing oxygen, and such oxygen compound as carbon dioxide, while the atmospheres of the outer planets contain hydrogen and such hydrogen compounds as methane and ammonia. Originally about two and one-half billion years ago, the atmospheres of all the planets were basically hydrogen and reduced atmospheres. This protoatmospheric composition dominated by hydrogen has been transformed in the course of many millions of years into one of oxygen and oxidized compounds by the effect of ultraviolet of solar radiation, but only on the planets relatively near the sun, namely on Venus, earth and Mars. These planets, therefore, form a kind of atmospheric "oxygen belt" in the planetary system. The atmospheres of the outer planets, moving beyond the effective reach of ultraviolet solar radiation, are still protoatmospheres preserved in a frozen state. They form a "hydrogen belt" of the primordial brand in the planetary system. But Jupiter, nearest to the sun in this outer belt, shows some indication of photo-chemical reactions in the upper atmospheric regions, manifested in green and reddish colorations,

which have recently been interpreted by Rice[4] as caused by free radicals of methane and ammonia in a frozen state.

In summary, this general ecological consideration leads us to the assumption of specific life favoring ecological belts in the planetary system such as an euphotic belt, biotemperature belt, liquid water belt, and oxygen belt. Because all of these belts are found in about the same region, they are therefore parts of a "general life zone" which we might call "ecosphere" in the solar planetary system and which is confined to the orbital range from Venus to Mars. (Fig. 2) This is the zone on the planets in which the kind of life now predominant on earth is conceivable. On the planets in the hydrogen belt, micro-organisms such as hydrogen-, ammonia-, methane-, and iron-bacteria, are conceivable; these are the kind which probably populated the earth during its protoplanet stage some two billion years ago and which we still find today in the pores of the soil and other poorly aerated spaces. However, the low temperature on the outer, so to speak, permafrost planets excludes the possibility of life in the hydrogen belt. The sun's radiation in this region apparently has not been sufficiently effective to change the atmospheric environment on these planets into a biologic climate.

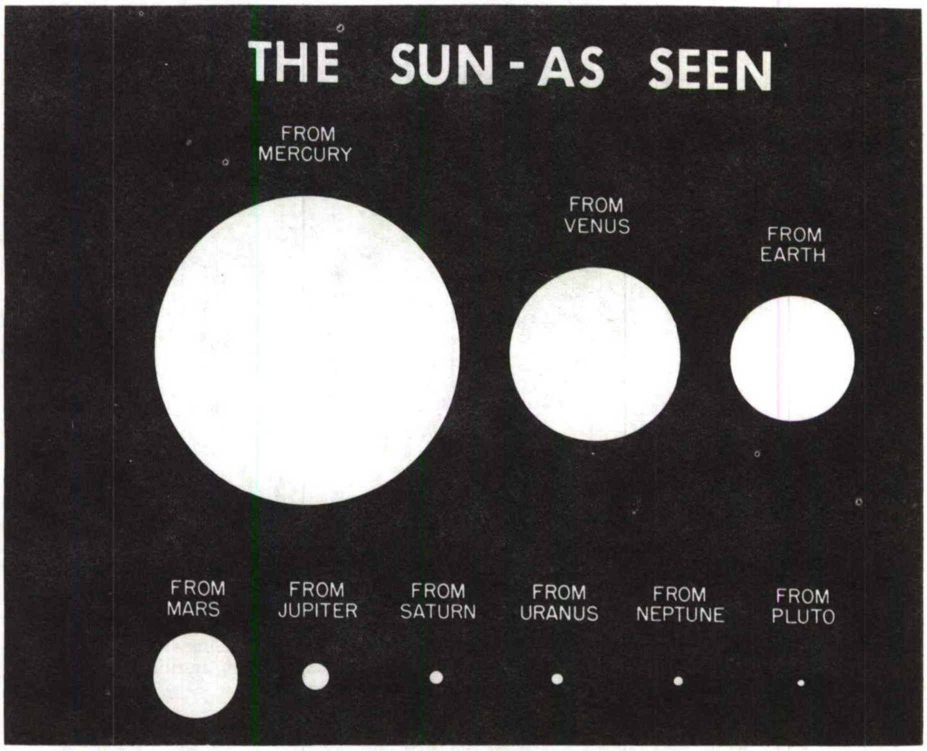

Fig. 1. Size of the sun as seen from the orbital distances of the various planets.

For all of these reasons, it would be ecologically impracticable to extend space operations beyond the well irradiated ecosphere to the outer planets with their hydrogen, methane and ammonia saturated atmospheres, and their arctic temperatures and surrounding midnight sun light conditions. But even the two ecologically acceptable planets, Venus and Mars, pose considerable medical problems. Because of

lack of time, I will omit a discussion of Venus, whose surface features are wrapped in mystery by dense clouds of carbon dioxide, and shall concentrate upon Mars. Of primary interest to the astronaut will be the question of the kind of atmospheric environment he would find there from the standpoint of human physiology, especially what protective measures he would have to take concerning respiration.

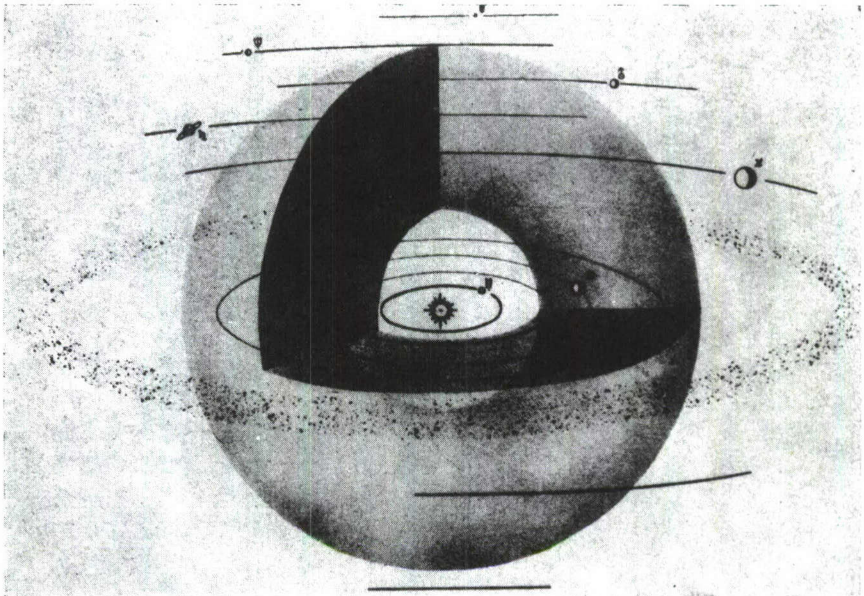

Fig. 2. Ecosphere or life zone of the planetary system comprising Venus, Earth, and Mars. Within this sphere lie the euphotic, biotemperature, liquid water and oxygen belts. All are essential to support life as we know it.

Atmospheric entry will pose fewer aerodynamic, aerothermodynamic and pertinent physiological difficulties than are encountered in the terrestrial atmosphere because of the lower air density. The most likely chemical composition according to de Vaucouleurs[7] is as follows: 98.5 per cent nitrogen, 1.20 per cent argon, 0.25 per cent carbon dioxide, and oxygen $<$ 0.12 volume per cent. The barometric pressure at ground level (there is, by the way no sea level on Mars because of the absence of open bodies of water) is about 70 mm. Hg. or 95 millibar. This pressure corresponds to an altitude of 55,000 feet in our atmosphere (Fig. 3). Barometrically, this altitude is the Mars equivalent level in our atmosphere. The oxygen pressure at ground level is probably lower than it is in our stratosphere.

Pilots flying at altitudes above 55,000 feet must wear pressure suits. The same would be required for an astronaut on Mars when he leaves the sealed compartment of his space ship. However, an air pressure of 70 mm. Hg. lies just within the critical border range in which a pressure suit, or simple oxygen equipment with pressure breathing, are a matter of dispute. Oxygen equipment with pressure breathing may be sufficient for shorter periods of time. Balke,[9] after spending six weeks at a height of 14,800 feet at Morococca, Peru, for acclimitization purposes, was able to withstand an altitude of 58,000 feet in a low pressure chamber for three minutes with pressure breathing only. A certain altitude adaptation of the astronaut can be expected

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if the air pressure in the sealed cabin is kept at a pressure of half an atmosphere during the trip. Be that as it may, a terrestrial explorer on Mars, wearing a pressure suit or pressure breathing device must always retreat, after an hour or hours depending on the efficiency of the equipment, into the more convenient sealed compartment of the ship, which should have its landing place in the lowlands because, with regard to the respiration equipment, every milimeter of Mercury of air pressure counts. Such a depressed area, for instance, is the Trivium Charontis, a dark greenish patch several thousand feet below the level of the surrounding desert.

In the event of a leak in the sealed compartment or in the pressure suit, the astronaut would encounter the same rapid decompression effects including anoxia and aeroembolism as the pilots do in our atmospheric region at about 50,000 to 55,000 feet. He would not, however, be endangered by "ebullism" a new term[8] for the so-called "boiling" of body fluids. This effect becomes manifest on Mars at an altitude of 13,000 feet which corresponds to 63,000 feet in our atmosphere. These are the essential points which must be considered in insuring physiological air and oxygen pressure for an astronaut. A factor which might facilitate the oxygen requirement and the mobility of the astronaut is the relatively low gravity on Mars, which is 38 per cent of that on earth.

The temperature in summer during the day in the equatorial regions may reach 25°C. After sundown when the temperature drops very quickly to —45°C., the space cabin must provide adequate protection. Harmful effects from solar ultraviolet rays can be disregarded. Even if they were not sufficiently filtered out by the martian atmosphere, the skin of the astronaut is always protected from sunburn by the respiratory equipment or by the cabin. Health hazards from primary cosmic rays are probably not to be expected because of the atmosphere's absorbing power. The same certainly would be true concerning meteorites.

The intensity of day light on Mars is lower than on earth but still in physiologically desirable limits. The color of the sky is probably whitish blue[2] due to scattering of light by the various hazy cloud layers. It might be that under this umbrella

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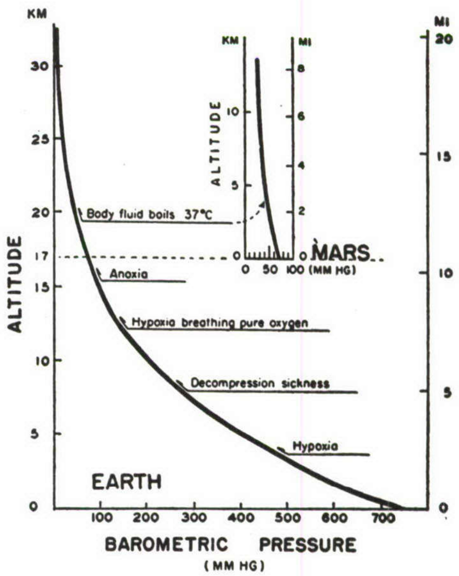

Fig. 3. Mars equivalent altitudes within the earth atmosphere. The altitudes and air pressures of the martian atmosphere are projected onto those of the earth. The curve shows points at which certain physiologic effects of decreasing air pressure are observed.

of whitish haze the sun would be invisible. Finally, an adaptation of the astronaut to a different day-night cycle is not necessary because the day-night cycle on Mars is only thirty-four minutes longer than that on earth. Such are the climatic environmental conditions that a terrestrial explorer probably will find on Mars from the standpoint of human physiology or, in other words, with regard to himself. A strange "second earth"!

Of particular interest for a terrestrial explorer on Mars will be the question: Does indigenous life exist on the planet itself? With this we touch upon the much discussed dark green areas in the equatorial

regions which show seasonal color changes and therefore have been interpreted as vegetation. Will the astronaut find that this is correct or will he find instead volcanic ash[3] or some hygroscopic inorganic material?[1] Recent spectroscopic studies seem to support the martian vegetation theory. The physical conditions are extremely severe with the exception of sufficient amounts of carbon dioxide and light. Such conditions, especially the extreme day-night temperature variations, according to terrestrial standards, could support only very hardy and cold resistant plants. We must, however, consider not only the climate as a whole but also the so-called microclimate near, on, and below the ground influenced by surface and sub-surface features, snow coverings, hollows, and caves which usually moderate the extremes of the macroclimate. Then there is the enormous capacity of life to adapt itself to abnormal climatic conditions. With regard to the specific environment on Mars we should consider the possibility of specific structures and properties of the plants for storing water, carbon dioxide and photo-synthetically produced oxygen. Such phenomena are well known in terrestrial biology. Strong absorbing power of the plant surfaces are infrared and reflecting power for blue could be imagined as a means for temperature control and protection against ultraviolet, respectively, if the latter is necessary. The pronounced bluish tint of the green areas on Mars might offer a hint in this respect. Protection against frost might be possible if the martian plants were able to develop some kind of antifreeze such as glycerol. We know that even terrestrial animal cells can survive temperatures as low as —70°C. when placed in glycerol solutions.

The opinion has been expressed by Tikhoff[6] that a terrestrial climate which comes nearest to that on Mars with regard to temperature, radiation and humidity is that found on the Pamir plateau, a high mountain desert in Central West Asia, or that on the high plateau of Tibet. As previously mentioned, the air pressure conditions on Mars correspond to those in the lower region of our own stratosphere. So if we combine the microclimate of the Pamir plateau or Tibet with the macro-climatic air pressure milieu of the lower stratosphere, we have an approximation of the environment on Mars. It is more severe than on the Pamir plateau but friendlier to life than our stratosphere because of its higher temperature during the day.

Such is the picture that can presently be drawn of an extraterrestrial environment most probably reachable from the earth. Whether or not this earthly conception corresponds to the martian reality, is a question that will probably remain open until a successful space operation to the green and red planet has been achieved. Until then, it will remain a common meeting place for discussion for astronomers, biologists, botanists and physiologists—in fact, for everybody.

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MECHANORECEPTORS, GRAVIRECEPTORS

by

Hubertus Strughold

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AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Mechanoreceptors, Gravireceptors*

Hubertus O. Strughold†

Randolph Air Force Base, Texas

Abstract

Attention is given to the sensing devices called mechanoreceptors or gravireceptors, located in the skin, in the skeletal muscles and in the connective tissue, which aid man's perception of the position and movement of his limbs and of the whole body. The anatomy of these mechanoreceptors, their physiological function under normal gravitational and zero-gravity conditions are discussed.

The human body is equipped with a number of sense organs which inform us about an exert reflex control upon the equilibrium of our body as a whole, at rest and in motion, and the position and movement of the limbs and other body parts.[16] The nerve endings in question, react to mechanical forces or stimuli; they are therefore referred to as *mechanoreceptors*. Those mechanoreceptors responding to stimuli, which are related to the gravitational force of the Earth, are called *gravireceptors* or graviceptors in the physiological literature.[15] This term is acceptable—not in the meaning that we were able to sense gravitational field forces, but rather—that we can perceive weight, a physical property of matter resulting from gravitational forces. In the publications dealing with this kind of sensory nerve endings, the gravireceptors of the centrally located labyrinth or more precisely of the otolith organ contained in the bony cavity of the inner ear, are discussed primarily. In contrast, little attention is given to those mechanoreceptors or gravireceptors which are distributed over the entire body, and which are found in the skin, in the skeletal muscles and in the connective tissue.

It is the purpose of this paper to bring these peripheral (extralabyrinthine) gravireceptors into focus by discussing their anatomy,[11] their physiological function under normal gravitational conditions,[14] and finally, their function under the condition of zero-gravity as it is encountered in space flight.

The Pressure Sense, Touch or Tactile Sense

The best known peripheral mechanical sense organ is that of the pressure or the touch sense of the skin. The sensations produced are called tactile and pressure sensations. The nerve endings of this skin sense are nervous plexuses around the hair follicles and the Meissner corpuscles in the skin of the tactile surfaces like the palms of the hand and the soles of the feet. The density of these presso- or tangoreceptors and of their corresponding so-called pressure points is about 20 per cm^2 on the hairy skin and more than 100 per cm^2 on the palms and soles, together totalling more than a half a million.[14]

The adequate stimulus for these sensory nerves is not the pressure as such, but rather a change in pressure resulting in a mechanical deformation of the skin.

The pressure sense nerves show rapid adaptation; after fractions of a second or a few seconds, the sensation fades, so that slight changes in the pressure at the same skin area will elicit new sensations. In contrast to the vestibular apparatus the pressure sense of the skin is free from disturbing after effects.

The reaction time of the pressure sense lies between those of hearing and vision or at about 160 milliseconds. This sense organ therefore reacts very quickly. The latent time of the sensation alone, the first part of the reaction time, ranges between 35 and 100 milliseconds.

The pressoreceptors of the skin play an important role in the perception of the position and movement of our limbs and of the whole body (especially in the active movements). When gripping an object, or when walking, we scan the surface of the object, or that of the terrain, etc. When one is swimming the stimulus of the resistance of water waves evoke pressure sensations in the skin. When flying an aircraft, the importance of the pressure sense lies in the sensations produced in the skin contact area with the seat, giving information about accelerations and decelerations during the passive movements of the body. Its importance for active movements lies primarily in handling the controls of the plane. In this function and others, the pressure sense is associated with two other sensory mechanisms, the muscle sense and the posture sense.

The Muscle Sense

The sensations originating from the muscles during passive and especially active movements are called muscle sensations and tension or tensile sensations.[1] The receptors are the so-called muscles spindles, found in all those muscles which fixate and move body masses especially in these of the limbs. The tension sensations

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† Chief, Department of Space Medicine, USAF School of Aviation Medicine.

of the muscles advise us of our weight as a result of gravitation and other accelerations. The muscle spindles also serve as receptors of the myotatic reflexes (Patellar reflex, etc.).[8] They are therefore the receptors of a gravi-sensory system and at the same time of a gravi-reflex system.

The Posture Sense

Besides the pressure sense of the skin and the tension sense of the muscles there is a third peripheral component in the sensomotoric control of our body and its parts. This can be deduced from experiments carried out by Du Mesnil de Rochemont,[3] in which the author served as one of the subjects. In these experiments the subjects, with eyes closed, had to move a finger against the spring of an ergemeter type movement recorder and one second later had to repeat this movement by a second one as precisely as possible. This was possible with a precision of about 95 per cent. Then by perineurial injection of tutocain the pressure nerves of the skin of the finger were eliminated, and finally the tension of the spring was changed each time between two movements so that the sensations from the muscles could not serve as a subjective measure for the extent of the finger movements. And yet, despite the anesthetic elimination of the pressure sense and the experimental elimination of the information from the muscle sense, it was still possible to repeat the first movement of the finger with almost the same precision. The information must have come from still other sensory nerves of neighboring proximal areas of the hand. Max von Frey[5] therefore assumed the existence of a third sensory mechanism which he called posture sense, because of its possible relationship to the postural reflexes described by R. Magnus.[10] The receptors are probably the Pacinian corpuscles which are found throughout the connective tissue surrounding and penetrating the muscles. They may be stimulated mechanically, when the muscles change their form during the movement. It is of special interest to us, that the Pacinian corpuscles which are found throughout the connective tissue surrounding and penetrating the muscles. They may be stimulated mechanically, when the muscles change their form duriing the movement. It is of special interest to us, that the Pacinian corpuscles are also found in the peritoneum, the membrane that covers and supports the intestines. These nerve endings are large enough to be seen with the naked eye, but their specific function has been somewhat overlooked. The reason may be that in contrast to the muscle sense and especially the pressure sense the excitations of the posture sense receptors do not fully trespass the threshold of consciousness; they remain more or less subconscious.

Thus, the perception of position and movement of our limbs seems to be thrice secured, namely, by the pressure sense of the skin, the muscle sense and the posture sense. These three peripheral mechanical sense organs together constitute, therefore, a functional unit in the perception and sensomotoric control of position and movement of body parts. This peripheral extralabyrinthine unit forms with the labyrinthine otolith organ a larger functional unit, a statokinetic control system, and is in this way integrated in the process of perception and sensomotoric control of position and movement of the whole body.[2, 4, 14]

In the physiology of the special senses we differentiate between exteroceptive and proprioceptive functions. They have an exteroceptive function insofar as they react to external stimuli and inform us about the outer world. They also may exert a proprioceptive function insofar as they inform us about the tension and—similar internal conditions—of the body and body parts.

In the case of the otolith apparatus and the pressoreceptors of the skin, the exteroceptive function seems to be more pronounced. In the case of the other mechanoreceptors the proprioceptive function is dominant. One of the environmental forces acting upon our body is the gravitation of the earth. When this force is nullified by another force (inertial force) with opposite direction, resulting in the state of null-gravity (as in space flight) the exteroceptive function of the gravireceptors is eliminated, but not necessarily their proprioceptive function which is predominant in the muscle sense and posture sense. This may explain why, in a free fall, a cat jumps well coordinated from a tree, or a diver from the board into the swimming pool, and why a pilot, during a parabolic flight, maneuver, handles the control of the plane well.[12] Aiming tests in studies by S. J. Gerathewohl in parabolic flight maneuvers in jet planes showed after several texts no significant deviations from the normal.[6] When the exteroceptive function of the gravireceptors is absent, it must be taken over by the exteroceptive organ par excellence: the eye. The exteroceptive function in space flight therefore depends entirely upon vision. The whole sensory statokinetic control of our body in this condition therefore is based on the exteroceptive function of the photoreceptors and the proprioceptive function of some of the mechanoreceptors. How far this will be efficient, can only be learned by the experiment.

The state of null-gravity is occasionally compared or even identified with floating in water. These two conditions have indeed one thing in common, which lies in the realm of the peripheral mechanoreceptors. During passive floating in still water, the pressure of the supporting water is distributed over almost the whole body and therefore sensations from the pressoreceptors of the skin do not occur or remain below the threshold of perception. And if the body has no foothold, tension sensations from the muscles of the legs are more or less absent. In contrast, during standing on solid ground or walking—in which cases the cutaneous contact area

with the supporting medium is relatively small—the pressure stimulus per unit area of skin resulting from the body's weight is great, and pressure sensations and muscle sensations therefore dominate the picture. It is the absence of the sensations from these peripheral mechanoreceptors, during floating in water, that makes people believe that this situation is identical with the state of null-gravity. This problem has been recently attacked experimentally in a swimming pool by L. A. Knight.[9]

Finally, I would like to touch upon another point which involves peripheral mechanoreceptors. It is a well known fact that the otolith organ has manifold reflex relations to organs controlled by the autonomic nervous system such as the stomach, the skin vessels, etc. It seems to me that the peripheral mechanoreceptors have similar reflex connections insofar as they are located in the peritoneum (Pacinian corpuscles). It might be that not only abnormal rhythmic excitations of the otolith organ play a role in the mechanisms of motion sickness but also those of these mechanoreceptors within the abdomen. After entering the gravity-free state the tension of the abdominal tissues attain a new equilibrium. Abnormal excitations from the nerve endings in the membranes around the stomach and intestines therefore are not to be expected. This might facilitate the tolerance of null-gravity, and a space version of motion sickness is not necessarily to be reckoned with in space flight.[7] However, the final answer to this can be given only as soon as we are able to produce the state of weightlessness for a number of minutes and hours.

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PROBLEMS OF RESPIRATORY METABOLISM IN SEALED CABINS

Hans G. Clamann, M. D.

Department of Physiology-Biophysics
School of Aviation Medicine, U. S. Air Force
Randolph Air Force Base, Texas
United States of America

Human tolerance to altitude is very limited. Since it is mainly the decreasing oxygen partial pressure which leads to this limitation with increasing altitude, maintenance of a suitable oxygen partial pressure is the means of permitting man to reach altitudes in aircraft far above his natural biological threshold. This threshold lies at about two thirds of the normal sea level pressure, corresponding to an altitude between 6,000 and 10,000 feet. By increasing the oxygen percentage in the inspired air above this altitude to 100 percent oxygen, we can raise this level to one-fourth sea level pressure or an altitude of 34,000 feet. A somewhat higher altitude may be attained by pressure breathing.

While this altitude constitutes a biological threshold, another method of sustaining normal oxygen pressure in an aircraft cabin finds its limitation by engineering reasons: The pressurized cabin. Here, a compressor should maintain a suitable pressure within the cabin and, simultaneously, keep a ventilating rate of about 10 cu. ft. per passenger per minute in order to replace the absorbed oxygen and to remove carbon dioxide, water vapor and odors. But above 80,000 feet (or three percent of sea level pressure) the atmosphere becomes so rare no compressor can maintain the required pressure ratio let alone the ventilation rate. These shortcomings are also apparent in the power plants of aircraft, where engines based on atmospheric combustion must be replaced by rocket motors that carry their own oxidizers.

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SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

Correspondingly, only a cabin which carries all oxygen needed, and in addition, means to remove all waste gases thus maintaining suitable environmental conditions, can be used for passengers above 80,000 feet. This is the definition of the "Sealed Cabin".

Basically, such a sealed cabin is the same if used for a rocket craft cruising at 100,000 feet or a space ship at a thousand miles distant from the Earth. Provided normal atmospheric pressure within the cabin, the pressure differential is not much influenced if the outside pressure is one percent of the atmosphere or complete zero. But it is yet uncertain for other reasons, if a pressure differential of about 15 psi can be maintained. As in present day aircraft, the structural rigidity may permit only 8 psi difference. With vacuum outside, the interior of the cabin has then to be kept at conditions equivalent to an altitude of 16,000 feet. To maintain sea level conditions, the atmosphere has to contain 40% oxygen.

To minimize leakage of the sealed cabin may be another reason to lower the pressure difference. In any case, the crew would have to live under conditions as they exist presently in military aircraft, only without oxygen masks. Very little is known about the effect of high percentage oxygen of normal partial pressure at long exposure time. It seems that only one such experiment on two men over three days at a simulated altitude of about 30,000 feet at 82% oxygen and 1% CO_2 has been performed (1). As theoretically to be expected, no pathological changes were found. Only gas extension in the gastrointestinal tract caused discomfort especially for one person.

The similarity of conditions in a sealed cabin with some in present day aircraft caused Strughold to coin the word "space-equivalent conditions" (2). Of course, there are some "true space conditions", such as weightlessness

and exposure to cosmic radiation. But these factors are not to be discussed in this paper.

What methods should be chosen to maintain suitable respiratory conditions in a sealed cabin depends almost entirely on the time the cabin has to stay sealed, or, in other words, upon the duration of the planned trip. After the Satellite Program of the IGY has produced direct information on some of the factors not too well known at present, the first step may be a manned rocket with a flight time of only hours. In this case, conventional methods of oxygen supply will suffice. Also, the absorption of CO_2 and water vapor can be accomplished by means of ordinary substances like baralyme, a mixture of Calcium- and Barium-hydroxide. It may be interesting to mention, that a normal man in a 50 cu. ft. cabin without any oxygen supply or means of absorption reaches 14% O_2 and 6% CO_2 after about 4 hours; water vapor saturation, of course, is obtained within the first quarter of an hour. The total pressure within the cabin will drop slightly due to the fact that more oxygen is inhaled than CO_2 is exhaled. Normally, this ratio $\frac{\text{vol. } CO_2}{\text{vol. } O_2}$, called the respiratory quotient or RQ, equals 0.85.

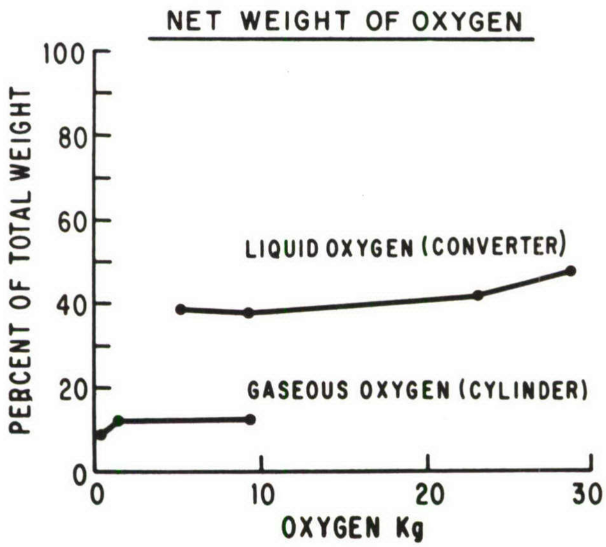
While there is little doubt as to the lower permissible concentration of oxygen, there is less agreement on the highest permissible concentration of CO_2, especially during long exposure times. This may be explained by the influence of the time factor. Otis and Chapin (3) spent three days in a "sealed cabin" in an atmosphere of 3% CO_2 and developed a definite decrease in their sensitivity to carbon dioxide as judged by their rate of ventilation and alveolar carbon dioxide tension. Two dogs were kept in the same room for two weeks in a concentration of CO_2 which rose gradually to 11%. They lost

their appetite and were in bad condition, but recovered rapidly when they were restored to normal condition. So, by adaptation, concentrations can be sustained which, in acute exposure, cause unconsciousness. For human, at rest or light work, a concentration up to 1 percent may be regarded entirely permissible even over long time.

At this point, it should be stressed, that the environmental conditions in a sealed cabin - as in any cabin of any aircraft - should be kept as much as possible at a level of comfort. Unusual alertness and short reaction time are necessary to fulfill operational requirements. These factors are more influenced by uncomfortable conditions than muscular force. As an example: The average number of mistakes by wireless operators at a room temperature of 95° F was more than four times as high as compared to 80° F (4).

With increasing time for a trip of a manned rocket, more pounds of equipment per passenger have to be taken aboard before the start. With respect to the performance and useful payload of the craft, the dead weight of all equipment should be kept low. It seems, that this dead weight is sometimes underrated. As an example, oxygen equipment will be discussed.

FIGURE 1


NET WEIGHT OF OXYGEN
PERCENT OF TOTAL WEIGHT
100
80
60
40
20
0
LIQUID OXYGEN (CONVERTER)
GASEOUS OXYGEN (CYLINDER)
0
10
20
30
OXYGEN Kg

In Figure 1, the net weight of oxygen, carried either in gaseous or liquid form, is shown as percentage of total weight of the container, not including any further equipment such as regulators, etc. Oxygen in gaseous form amounts to 12 percent of the total weight, liquid oxygen from 39 to 47 percent. There is a slight increase in economy toward the units carrying higher weight. But since there exists a limit as to the size of such containers, not much higher economy may be expected.

Fortunately, the biggest unit carrying 29 kilograms liquid oxygen will last one man about a month. The sealed cabin, in contrast to normal aircraft, is not affected by the constant evaporative loss of liquid oxygen, since the oxygen will remain in the cabin.

As for chemical removal of carbon dioxide and water, in general, various possibilities have been discussed, for instance, by Bowman (5). For presently used substances, the necessary quantities are outlined in a recent report (6). So, for one man and one day, about three kilograms of soda lime or baralyme are required to absorb the one kilogram of exhaled CO_2. Lithium hydroxide requires somewhat less weight. For this calculation, not the theoretical capacity of absorption, but the actual capacity has been considered.

Besides taking in account the actual capacity, here, as in O_2 equipment, the weight of the necessary auxiliary equipment has to be added. For minimum weight penalty, a uniformly mixed granular bed containing the required quantities has to be arranged. Furthermore, one or more blowers have to be installed. These same considerations are valid for solid dehumidifiers. Without going into details, once more it should be emphasized, that any theoretical assumptions have to be confirmed by experiments, in order to arrive at the actual weight of a complete system.

Basically, no special difficulties should exist in a sealed cabin for some days or even weeks. But for travels in the order of months or even years, as outlined in Von Brauns "Mars Project" it will be impossible to carry along the vast quantities required for storage.

A more general aspect of the sealed cabin may here be helpful for further discussion. Thermodynamically, a sealed cabin with the crew enclosed constitutes a system which converts higher potential chemical energy to a lower degree of chemical energy, the difference in energy dissipated as heat. Neglecting the theoretical loss of mass constituted by this energy, the cabin as a whole obeys the law of conservation of mass. Thus a sealed cabin incorporated in a space-cruising rocket must not release any waste, since this would change the weight of the craft and possibly alter its course. In addition, burning of waste would require oxygen, drying of material into the surrounding vacuum constitutes a loss of water, and shooting of dried material out of the ship requires energy and may create artificial meteorites, potentially harmful to other spacecraft. An exception may exist for crafts cruising for shorter times, i.e., in orbits around the Earth, which can afford to discard waste in gaseous form.

Thus, visualizing the sealed cabin as a self-sustaining unit, emphasis should be put on reversible processes. Bowman (5), for instance, mentions a complete cycle by using calcium oxide for water absorption, the produced calcium hydroxide for carbon dioxide absorption, and by heating the finally obtained calcium carbonate to remove carbon dioxide and regain calcium oxide. This system, of course, would regain only the absorptive substance and still require to remove the gases.

The idea to produce a complete cycle for oxygen, carbon dioxide and water by means of a biological system, namely plants, which also may deliver food, is indeed tempting. Scientists working in the field of photosynthesis seem to have been among the first to attack this problem using algae. But their viewpoint was directed rather to produce food by solar energy (7, 8) than toward the requirements of a sealed cabin. Shortly afterwards the idea to use algae as gas exchangers for submarine came up (10), and consequently, for space ships.

Before we discuss the algae as energy converter for the sealed cabin, we have to look closer to our primary energy converter: Man. In order to obtain a quantitative picture, a "standard man" has been created. His respiratory-metabolic data are based upon average values obtained from various textbooks of physiology. The data are shown in Table 1.

TABLE 1

Daily Metabolic Turnover

(Man 70 kg. RQ = 0.82. Food: Protein 80g, Carbohydrate 270g, Fat 150g)

	Input		Substances		Output		
	%	grams	603-liters-496		grams	%	
Gases	24.04	862	Oxygen	Carbon Dioxide	982	27.39	
Liquid	61.37	2200	Water-	→ 2,200 → 342	2542	70.91	(= plus 9.54%)
Solids	13.95	500	Food	Urea	27	0.75	
	0.64	23	Salts	Salts	23	0.64	
			Unaccounted for		11	0.31	
	100.00	3585			3585	100.00	

plus 2830 Kcal

The first surprise may be the near perfect balance in input and output - only 0.31% of its output are unaccounted for. Actually, such balance does not exist for such a short time as one day. But over a length of time, seen statistically, a normal healthy adult keeps his weight fairly constant, since the law of conservation of mass is valid for man too.

The next remarkable fact is, that the human organism constantly gives off more water than it takes up. In our standard man, the excess amounts to almost ten percent. The simple reason for this excess is the partial conversion (oxidation) of food to water. Consequently, in a sealed cabin the amount of free water increases with time, even if the water is recirculated.

We will now consider the respiratory-metabolic processes of our potential re-converster, the algae.

TABLE 2

<u>Algae Metabolism</u>

(Dry Algae: 50% Protein)

<u>Photosynthesis</u>

Light Energy

									RQ	$\frac{1}{RQ}$
Mol. Weight	1 44	CO_2	plus	1 18	H_2O	$\xrightleftharpoons[\text{(Respiration)}]{h\nu}$	CH_2O plus	1 32	O_2	1	1
"	3 132	CO_2	plus	2 36	$H_2O + NH^+$	with ammonium ion $\longrightarrow$	$C_3H_7O_2N$ +	3 96	O_2	1	1
"	3 132	CO_2	plus	3 54	$H_2O + H^+ + NO^-_3$	with nitrate $\longrightarrow$	$C_3H_7O_2N$ +	5 160	O_2	0.60	1.67

Algae, as any other green plant, convert carbon dioxide to carbohydrate by means of the reducing power arising from the photochemical oxidation of water (first line in Table 2). The respiration proper goes in the opposite direction, but is quantitatively much smaller and is traceable only in the dark. Since one unit of volume carbon dioxide absorbed corresponds to one volume oxygen produced, the respiratory quotient $\frac{\text{vol. } CO_2}{\text{vol. } O_2}$ equals 1. If we make the substance produced the numerator, as we do in the RQ of man, we would have $\frac{\text{vol. } O_2}{\text{vol. } CO_2}$ which is called the Photosynthetic Quotient. It equals $\frac{1}{RQ}$.

In many plants, the RQ is close to one. But in algae, such as Chlorella where the dry substance consists of 50% protein (8), we have to expect other synthetic processes indirectly related to photosynthesis, which lead simultaneously to the production of proteins, lipids and other organic compounds. Two such synthetic processes (second and third line) concern the formation of alanine from ammonium ion and nitrate (11), respectively. Therefore, we should expect a resultant RQ somewhat lower than 1. And indeed, Myers has measured RQ's of 0.8 and 0.9 feeding Chlorella with nitrates or urea, and recently found even R. Q.'s = 0.7.

Since algae in the first place were considered to produce food by means of solar energy from inorganic raw material and in the second place to produce oxygen as gas exchangers by means of artificial irradiation in submarines, almost all attention was directed to their effectiveness in the utilization of light.

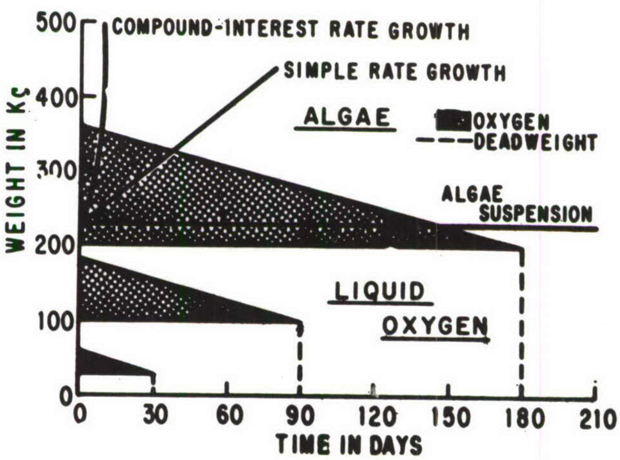
Chlorella is most effective in a 1% suspension in water. For the production of 25 liters of oxygen per hour, 2.3 kg of wet algae in 230 liters of

water are necessary according to Myers (12). Others regard a smaller amount as sufficient (11). Actually, Chlorella produces so much oxygen only in a rapidly growing process, multiplying in the first hour 4 to 8%, depending on supply of light and CO_2. Above a light intensity of 500 foot candles and 0.1% of CO_2 the growth rate does not further increase. Growing at a compound interest rate, 1 kilogram of algae would increase to 2.6 kg in one day. In any case, a certain amount of algae has to be removed at intervals.

Here is a point where some differences between the submarine and the sealed cabin are evident. For the submarine the necessity to remove algae and the weight play a minor role. For a sealed cabin with its delicate biological balance such factors are decisive.

Regarding, first, only the capability of Chlorella to produce oxygen, we may plot the weight of algae versus the weight of liquid oxygen systems.

FIGURE 2



(Figure 2). Actually, the accessories needed for the algae (tanks, pumps, light systems) are omitted because their weight is very hard to estimate. The estimate of Bowman seems too small. It is seen that for a time of 180 days the weight of the liquid oxygen system is of the same order as that of the algae. While the weight of the oxygen system decreases by giving off its content, the weight of the algae increases by growth somewhere between the upper curves.

Can Chlorella fulfill its purpose as gas exchanger for a sealed cabin? Certainly we expect the algae to do this for oxygen and carbon dioxide. In Table 3 the amount of gases produced and absorbed is presented

TABLE 3

Gas Exchange	RQ =	Man 0.85	Algae 0.70	Difference in Gas Balance
Balanced for O_2	O_2	1	1	-
	CO_2	0.85	0.70	plus 0.15
Balanced for CO_2	O_2	1.18	1.43	plus 0.25
	CO_2	1	1	-

with a RQ of 0.85 for man and 0.70 for Algae. Conventionally, the balance is set first for oxygen, in other words the algae produce as much oxygen as man consumes. In this case, 15% of the carbon dioxide (with reference to the unit of oxygen) cannot be consumed by the algae. If the balance is set for complete removal of carbon dioxide by the algae, a surplus of oxygen is left. Since this situation is certainly preferable to an excess of CO_2, the somewhat surprising fact emerges, that our algae system has to be balanced rather for CO_2 than for O_2.

If we try to extend this balance for water also, we encounter more difficulties. Actually, since we cannot change the RQ of man substantially,

and the RQ of algae probably only moderately, a complete biological balance in such a small system as even a large sealed cabin seems extremely difficult.

TABLE 4

Attempted Balance in O_2, CO_2, and H_2O

between Man and Algae (in arbitrary weight units)

			Balanced for O_2			Balanced for CO_2	
	RQ	O_2	CO_2	H_2O	O_2	CO_2	H_2O
Man	0.82	1.	1.14	0.40	0.88	1.	0.35
Algae	1.00	1.	1.38	0.56	0.73	1.	0.41
Difference	Weight	-	-0.24	-0.16	-0.15	-	-0.06
	Percent	-	-17	-29	-17	-	-15
Man	0.82	1.	1.14	0.40	0.88	1.	0.35
Algae	0.60	1.	0.83	0.34	1.21	1.	0.41
Difference	Weight	-	+0.31	+0.06	+0.33	-	-0.06
	Percent	-	+ 37	+ 18	+38	-	- 15

Table 4 presents an attempt to reach as closely as possible a balance between the "Standard man" and algae with various RQ's.

Our last goal, to extend a biological equilibrium on the nitrogen metabolism, seems also extremely difficult. With a simple rate of growth of 4% per hour, 2.3 kg wet algae would produce 23 grams dry weight per hour or 24 x 23 grams per day = 552 gram or, with 50% protein, 276 gram protein per day. Our standard man consumes only 80 gram per day. Maybe he could be induced to consume more protein, which in turn would yield more urea to feed the algae.

Algae have been already processed successfully into various kinds of food (9). But it will possibly require more than one French cook, to produce meals only from algae which satisfy the taste over a long time.

Summary: Above 80,000 feet flying altitude, a complete sealed cabin is mandatory. In order to keep the storage on oxygen, carbon dioxide and water absorbers as small as possible, regenerative and recirculation processes have to be developed. Due to the fact of metabolic oxidation, the amount of free water will increase.

Biological gas exchangers such as algae seem to be very attractive. But on a close analysis, it becomes evident that a true balance between man and algae is extremely hard to obtain. Future studies - at least with respect to the problems of the sealed cabin - should be directed more toward such balance rather than to light utilization by the algae.

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THE ENVIRONMENT OF SPACE IN HUMAN FLIGHT

by

Charles A. Berry

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HEADQUARTERS
SCHOOL OF AVIATION MEDICINE, USAF
AIR UNIVERSITY
RANDOLPH AIR FORCE BASE, TEXAS

THE ENVIRONMENT OF SPACE IN HUMAN FLIGHT

CHARLES A. BERRY, MAJOR, USAF(MC)
Department of Aviation Medicine
School of Aviation Medicine
Randolph AFB, Texas

Since the dawn of his existence man has been conquering his environment whether it be land, sea or air. The vertical frontier described by General Benson now stands with an open door and beckons us on to the outer reaches of our planet's atmosphere and space. The very thought of space has long occupied man's imagination and still has produced an awesome mental picture of a black, cold, hostile area of nothingness far out on the vertical frontier. As flight surgeons and specialists in Aviation Medicine, we are concerned with the hazards this hostile environment presents for our space pilots of the future. In present day aviation medicine our concern has not been limited to the lower atmospheric shells, but has encompassed brief exposures to the upper borders of the stratosphere (126 M') by Kincheloe. (M'= 1000 ft.) Thus Aviation Medicine has already been confronted with "space" flight problems and needs only to expand its interest further vertically to cope with the problems of true space flight. It is the purpose of this paper to define "space" as an environment for man and to indicate that present day operations are carried on in "space" as far as man's physiology is concerned.

Space Equivalence

The conventional atmospheric chart showing the level of the exosphere with its few remaining ions of air at 600 miles must be

discarded when we consider man. Dr. Hubertus Strughold published a paper in 1954 in which he discussed the concept of "space equivalent" altitudes. This study delineated a zone of "physiological insufficiency" starting at an altitude of 10M' and extending to 50M', a "partially space equivalent" zone extending from 50M' to 120 miles and a "total space equivalent" zone above this altitude. See Figure 1. The loss or change of certain of the atmosphere's properties create difficulty for man then at very low altitudes.

Oxygen: The reduction in overall pressure and resultant decrease in partial pressure of oxygen creates a problem in supplying this vital element. The problem has existed since the first days of balloon flight and numerous means of providing adequate oxygen have been developed. These have been summarized in Figure 2. The partial pressure is such that from 10-34M' mixtures of ambient air and oxygen may be supplied by an automatic regulator and provide adequate oxygenation. At 34M' the oxygen partial pressure in the lungs when breathing 100% oxygen is the same as when breathing air at sea level. At altitudes of 34-40M' 100% oxygen will suffice, but from 40-50M' pressure must be added. At 50M' the ambient pressure reaches levels where, due to alveolar pressures of the various gases, the physiological effect is the same as if there were no oxygen and the time of useful consciousness reaches a constant of 12-15 sec.

It becomes necessary to supply the oxygen under even more pressure. In order to prevent pooling of fluid in the extremities as well as other complications, counterpressure must be supplied to the body. A

series of partial pressure suits has been designed and these have provided protection up to 200M' for prolonged periods. Though his garment will protect against the space equivalent condition of low oxygen tension it still places a man at the equivalent of 40M' breathing 100% oxygen. A better and more physiological answer would seem to be the full pressure suit recently demonstrated by the Aeromedical Laboratory. Though there is no doubt this garment will protect man from the lack of oxygen, work still needs to continue to improve the mobility, strength and comfort in order that man may withstand the rigors of a walk on the moon.

Total Pressure

Dysbarism: The well known decrease in pressure with altitude creates many problems for man due to the gases in his body responding to the laws of Boyle and Henry. You are all familiar with the expansion on ascent and contraction on descent of the gases in the middle ear and sinuses, a phenomenon routinely experienced even in conventional airline flight. The entire symptom complex resulting from a decrease in total atmospheric pressure we have termed dysbarism. In addition to ordinary expansion of gases in the ear, sinus, and intestine, the reduction in pressure releases nitrogen which is in solution in the blood and tissues. This bubble release probably combined with other mechanisms produces the more severe dysbarism symptoms of bends, chokes, various neurological disorders and neurocirculatory collapse and death. Though deaths have been few both in the training (pressure chamber) and

operational (aircraft) situation, we are seeing more severe cases which disable the pilot, at least temporarily and perhaps longer. (2) Denitrogenation by breathing 100% oxygen at ground level for approximately 2 hours has been a good prophylactic measure, as well as the more obvious one of maintaining the microclimate about the man at an altitude below 30M'. Symptoms of severe dysbarism are rarely seen below this altitude.

Ebullism:

Another effect of the decreased total pressure which is of concern to the human going to space is the so called "boiling" of body fluids. Ward (14) has discussed the factors determining the onset of this phenomenon and suggested the term "ebullism" because boiling in common usage carries the implication of an increase in temperature. It is important to realize that vaporization of body fluids begins at ground level and varies for different parts of the body with temperature, decreasing atmospheric pressure and the solute content of the body fluids. Beischer (1) has reported studies on various frogs and worms exposed to 5 mm Hg. pressure for several hours. Marked dehydration occurred due to vaporization and evaporation of body fluids at the surfaces. These animals were not explosively decompressed however. Intravascular ebullism will surely occur in man with acute exposure to altitudes approximating 63M'. As the total pressure at this altitude is only 47 mm Hg. - equal to the commonly accepted value for water vapor pressure, this altitude (63M') has been felt to represent the

absolute demarcation line for the onset of ebullism. This is not so however as temperature and the body fluid solutes may allow this to vary between 63,000' and 67,000'. Intrathoracic water vapor producting a vapothorax may form at altitudes as low as 61,500'.

Ozone: Spectrographic measurements both in this country and in Germany have revealed an area of increased ozone content greatest between 70 and 100M' with little or none above 120M'. (6) This ozone is produced by the action of ultraviolet, in wave lengths less than 2000 Angstroms, on ordinary oxygen. The atmospheric concentration varies with the season and with geographic location as shown in Figure 3. The concentration is lower in the fall and higher in the spring. What significance does this hold for man? Clamann (4) has reported studies on the physiological effects of ozone in five human subjects. Though there were great individual differences in sensitivity, irritation of the respiratory tract was observed at concentrations as low as 0.6 ppm for exposure times of 30 min. Gross changes in respiratory function (50% reduction in vital capacity and onset of pulmonary edema) were noted after exposures to 6 ppm for 1 hour. Its toxicity is graphically illustrated by the maximum allowable concentration (for an 8 hour daily exposure for a year) being 0.1 ppm compared to 100 ppm for carbon monoxide and 1 ppm for phosgene or chlorine. The effect of ozone on rubber is well known and intermittent exposure of equipment such as oxygen masks to even 1 ppm for 100 hours has resulted in severe deterioration. This points up the need to use such ozone resistant products as neoprene, the silicones or hypalon.

The newer compressors are capable of utilizing ambient air for cabin pressurization up to an altitude of 80M'. As exposure to heat for 1 second will destroy ozone, it has been hoped that in passing ozone laden air thru the compressor the resultant heat would reduce the ozone content to zero. Unfortunately the very efficiency of these new compressors depends on their speed, thus reducing the contact time of air with heat to a level where less than 50% of the ozone is destroyed. Though this absolute concentration is small, it is increased as much as 10 times by returning it to near sea level conditions in the cabin. Some filter design will be necessary. The photochemical production of nitric oxide (NO) in the region of roughly 300-400M' has not been as well studied.

Cosmic Radiation

Above approximately 120,000 ft. man will be exposed to the heavy primary cosmic rays. These rays are mainly protons with some nuclei of helium and other elements up to at least iron and cobalt. They arrive from all directionsin almost an equal number, so the cosmic ray flux may be considered to be of uniform density at all points. Each of these extremely high energy particles eventually strikes a nucleus of another atmospheric particle creating a veritable avalanche of secondary particles. It is believed that the effects of this radiation on man will be like that of other known radiations (x-ray - gamma etc).

Meteors:

Above 400,000 ft. any vehicle will be exposed to the hazard of collision with a meteor which could range in size from dust particles to many tons. Whipple estimates that an earth satellite with a radius of 20 inches and skin thickness of 0.5 mm aluminum will be punctured once in five days. (9) This is more frequent than estimates made earlier by Whipple (15), and also by Grimminger (7) who estimated that a 1000 sq. ft. area would suffer a penetration hit only once in about 15 years. Erosion of vehicle surfaces by meteoritic dust may be a more common hazard.

The satellite projects should provide much more accurate information in this regard. The suggestions for a meteorite bumper (15) and compartmentation of the cabin (10) are possible means of protection.

Solar Radiation

Light: Ultraviolet radiation, unscreened by the ozone layer, produces a serious sunburn hazard to unprotected man above 120-140,000 ft. Ordinary glass and most plastics are good absorbers of this portion of the spectrum (3000 to 2100 Angstroms).

The twilight of space has been reported by observers in present day balloons and aircraft. At 400,000 ft. this loss of scattering power, due to the small numbers of molecules available, reaches space equivalence. This same scarcity of air molecules prevents the propagation of sound waves at this altitude.

Heat: If a body is maintained at rest in relation to the ambient air, a pure radiation equilibrium could be attained at an altitude of approximately 30 miles. At the expected speed of an orbital vehicle the radiation equilibrium would not be reached under an altitude of 150 miles. (8) The temperature equilibrium will depend upon many variables such as the vehicle's position in relation to the other radiating bodies (the sun and the earth) its movement (spin or wobble), the nature of its surface and its thermal capacity per unit area. The vehicle may face space, the sun and the light or the dark earth all in one orbit. Piccard (11) reported difficulties in this regard as early as 1931 when he had painted one side of his balloon gondola black and left the other shiny. He hoped to control the temperature of the gondola by rotating the required side toward the sun. The rotation mechanism failed however with the black side toward the sun and the temperature inside the gondola rose to 95-104° Fahrenheit. If the vehicle's orbit could be arranged to coincide with the great circle dividing the earth into its sunlit and dark hemispheres it would remain in the sun's illumination. Buettner (3) calculated the equilibrium temperatures of white, black and polished aluminum surfaces both facing the sun and then facing the sunlit earth and the dark earth. These figures show a higher equilibrium temperature for the polished aluminum surface than for the painted white or black, thus suggesting painting the surface of spacecraft. Man's tolerance to heat requires further testing, but he should not even be expected to endure the dermal pain produced by temperatures of 44.8°C (3). The problems of heat produced by speed will be discussed in another paper.

Weightlessness:

This peculiar phenomenon has received much attention lately and has been studied by producing it experimentally in parabolic flight in jet aircraft. The problems of eating, drinking, performance etc. seem solvable. This is the one condition mentioned thus far which is not a function of altitude or distance from the earth's surface. Though the force of gravity does decrease with increasing distance from the earth's surface it will always exert some minute force. The density of the atmosphere acts only to limit the duration of the gravity free state. The condition of weightlessness must be produced by the speed of the vehicle being such that centrifugal force balances the gravitational pull of the earth.

Sealed Cabin:

Many of the above mentioned effects have been problems faced by present day aircraft, and the pressurized cabin was introduced as a means of protection. The continued development of protective equipment attests to the fact that these cabins, like most man made devices, are not foolproof or 100% trustworthy. Even if they were this reliable, the use of such a pressurized cabin is limited by altitude, the pressure differential, and the heat produced by trying to compress the thin air. The only solution seems to be placing man in a sealed cabin where his microclimate can be totally controlled. The integrity of even this device may be compromised, however, most likely by meteorite penetration. Thus a basic decision must be made as to where the line will be

drawn on providing safety and emergency equipment. Should we try and is it possible to save the man if the best designed cabin system should fail? Our humanity and our pride as flight surgeons demand that we do the utmost to provide every possible means of protection against the hostile environment. Thus even in the sealed cabin a pressure suit will be necessary in case of cabin failure and later to allow any exploration outside the cabin.

The sealed cabin must be a complete synthetic world independent of the ambient atmosphere. The most critical function of this little world will be the providing of adequate oxygen and the removal of carbon dioxide. Liquid oxygen will most likely be used in our early ventures into space. An average value of one cubic foot of oxygen per hour must be available.

The deleterious action of carbon dioxide on mental function is a time - concentration phenomenon and for indefinite periods should be maintained below 1% of ground level atmospheric pressure (8 mm HG.). Chemical absorbents such as sodium hydroxide, soda lime and other alkalies are the only practical methods of removal at present. Their weight will preclude their use on long flights however. Photosynthesis by using a live system - algae, and photochemical methods of decomposition of carbon dioxide are under consideration for the future.

Temperature and humidity control must be provided by advanced air conditioning techniques. Odor removal is purely aesthetic for calculations have shown the first physiological effect of flatus in a 100 cu. ft. cabin occupied by one man would be tearing of the eyes due to

hydrogen sulfide. It would take 2000 days of exposure to reach fatal H_2S levels.

Waste (urine and feces) disposal and recycling have been investigated recently at the School of Aviation Medicine. Filtration and evaporation of urine for reuse have shown promise.

The psychological problems presented by the exposure of man to an isolated, uncomfortable void seem to be more formidable than the physiological problems. A recent twenty-four hour "flight" in the School of Aviation Medicine space cabin simulator pointed up such problems as the extreme loneliness experienced even though the subject knew the simulator was still on the ground.

The stresses to be encountered by the "space" pilot are thus many, and these stresses are summarized in Figure 4. Careful selection for both physical and mental attributes will be necessary. Testing all possible stresses on various simulators will be a valuable tool in this selection.

The problems presented by space as an environment for human travel are thus extensions of those encountered in present day flight. The environment of the sealed cabin necessary to protect the space traveler against the hazards of the ambient environment will itself produce new problems such as isolation, but this too has been described in jet flight as the "break-off phenomenon." (5) I have great faith that man's adaptability, the engineers ingenuity and the flight surgeon's ability to meet and solve the problems of maintaining man's homeostasis in all environments will at last conquer the vertical frontier.

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FIGURE 1

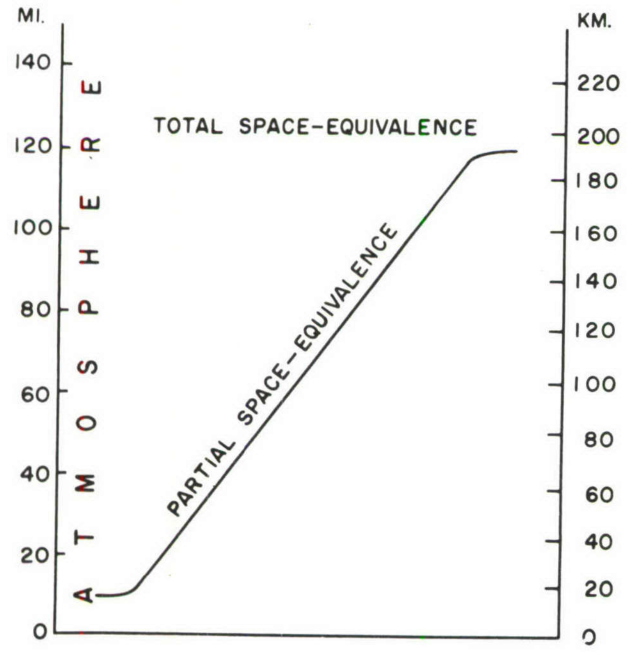


FIGURE 2

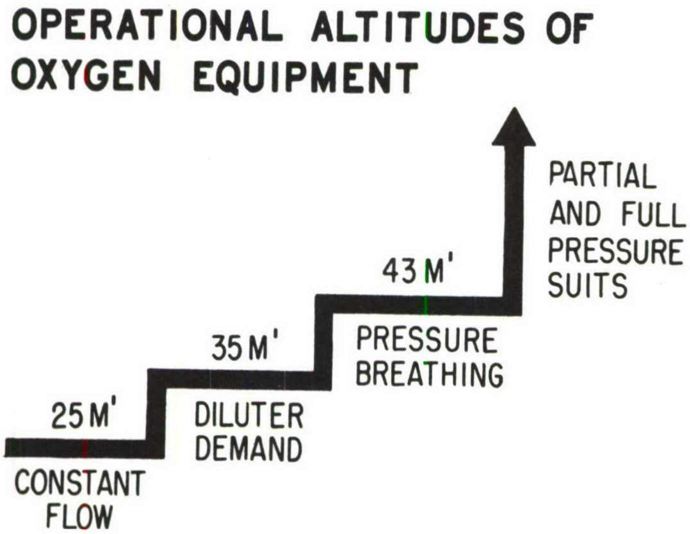
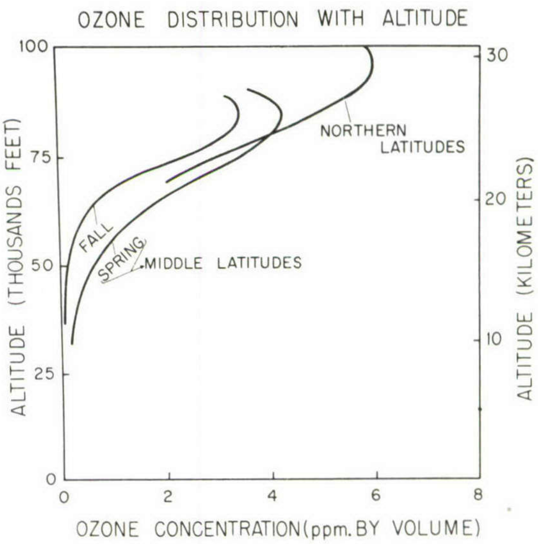


FIGURE 3



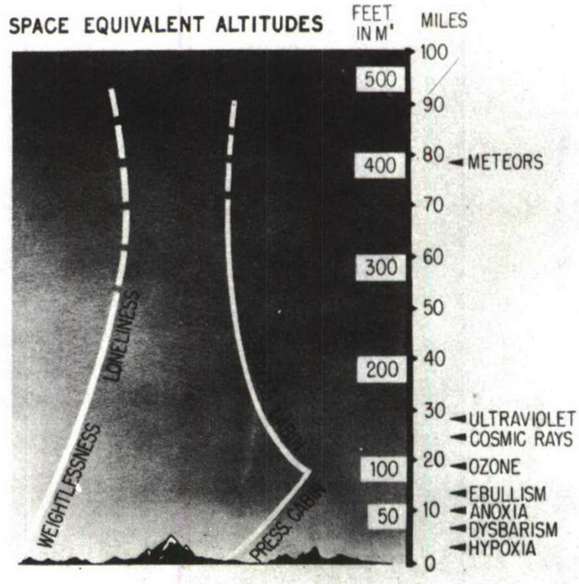


FIGURE 4